Celestial enlightenment: eclipses, curiosity and economic development among pre-modern ethnic groups *

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Abstract

This paper revisits the role of human capital for economic growth among pre-modern ethnic groups. We hypothesise that exposure to rare natural events drives curiosity and prompts thinking in an attempt to comprehend and explain the phenomenon, thus raising human capital and, ultimately, pre-modern growth. We focus on solar eclipses as one particular trigger of curiosity and empirically establish a robust relationship between their number and several proxies for economic prosperity: social complexity, technological level and population density. Variation in solar eclipse exposure is exogenous as their local incidence is randomly and sparsely distributed all over the globe. Additionally, eclipses' non-destructive character makes them outperform other uncanny natural events, such as volcano eruptions or earthquakes, which have direct negative economic effects.

We also offer evidence compatible with the human capital increase we postulate, finding a more intricate thinking process in ethnic groups more exposed to solar eclipses. In particular, we study the development of written language, the playing of strategy games and the accuracy of the folkloric reasoning for eclipses.

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1 Introduction

Curiosity is a natural precursor of human capital insofar as questions precede answers. Yet the literature on human capital formation has paid scant attention to this predecessor, and little is known about its implications for economic growth. Natural phenomena are an obvious candidate for studying the arousal of curiosity and its bearing on development through human capital: humans have always sought to comprehend the world around them, prompting deeper and more intricate thinking. Hence, as people become more exposed to strange events and ponder their causes, they gain a comparative advantage in thinking, which eventually translates into superiority in human capital. Most major natural shocks, however, entail mass destruction. Hence, events such as earthquakes or volcanic eruptions couple the intellectual challenge with an economic cost, implying opposite effects on human capital and growth. A notable exception is solar eclipses: harmless events that rank amongst the most impressive celestial phenomena, sparking people's curiosity to understand why day turns into night.[1] In this paper, we argue that eclipse frequency is related to increased levels of economic development among pre-modern ethnic groups. We maintain that human capital levels increase with eclipse exposure as people attempt to explain these phenomena, which in turn has positive consequences for development outcomes.

We validate our conjecture using several indicators of economic prosperity available in Murdock's Ethnographic Atlas (1967) and in the Standard Cross-Cultural Sample which we combine with eclipse data derived from Espenak and Meeus (2006) and Jubier (2019). In particular, for each ethnic group listed in the Atlas, we count the number of *total solar eclipses* visible from within its traditional homeland boundaries. Such eclipses occur when the Sun, the Moon and the Earth perfectly align on the ecliptic. On Earth, day turns into night as it enters the Moon's shadow. The darkening, however, is very local: a strip less than 160 km wide that affects vast swaths of the Earth in a west-east motion. At the ethnic homeland level, the average time between two eclipses is around 65 years while the average number of eclipses is approximately 70 over a period of 3500 years.[2] Eclipses' non-destructive nature distinguishes them from other natural events, such as earthquakes, floods or eruptions, and allows us to isolate the role of human capital on economic growth: after an eclipse, all that remains is a feeling of

[1] Murray (2014, p. 240)

[2] On average, there is one total solar eclipse approximately every 18–20 months somewhere on Earth. In a given location, total solar eclipses are separated, on average, by four centuries.

restlessness. In contrast, harmful events can divert attention and resources to more imperative reconstruction efforts and destroy human capital, delaying growth.

Based on Diamond's (2017) idea of social complexity increasing with development, we show that ethnicities more exposed to solar eclipses display a more sophisticated organisation. Moreover, the effect of eclipses extends to other measures of economic development: society's technological level and population density. A series of robustness tests considering additional social and geo-climatic characteristics confirm the previous association. Lastly, we show that introducing alternative potential drivers of curiosity does not affect our results.[3]

Lastly, we present compelling evidence tackling the mechanism we propose. In light of the beneficial effects of curiosity on human capital we postulate, we analyse the effect of eclipses on two indirect measures of human capital: the development of a written language and the playing of strategy games. Furthermore, if our conjecture is correct, we shall expect a better understanding of eclipses among the groups that experienced more. Following Michalopoulos and Xue (2019), we assess this possibility by studying the folkloric explanation ascribed to eclipses.[4] We show that, as the number of eclipses increases, the likelihood that tales explaining them include the Sun the Moon raises. This is to the detriment of more naive explanations depicting eclipses as acts of animals or gods.

Our paper is similar in spirit to Severgnini and Boerner's (2019) and Boerner et al.'s (2019) idea that solar eclipses induce curiosity. However, the authors leverage eclipses as an instrument to study the adoption of mechanical clocks in mediaeval Europe, a time when the exact mechanism underlying them was well understood, and clocks provided a more precise tool to time their occurrence. On the contrary, we are interested in relating the frequency of unknown, intellectually challenging phenomena (as eclipses were during the early stages of development) to economic prosperity through increases in human capital as people devote mental resources to their understanding. With this study, we contribute to the research on the long-run determinants of growth, in particular, on the role of human capital. The empirical literature on the topic coincides in its importance. However, the bulk of the analyses refer to the industrial and post-industrial periods —Galor and Moav (2006), Barro (2001) and Hanushek and Woessmann

[3]In particular, we focus on earthquakes, volcanic eruptions, lunar eclipses and partial eclipses. However, a rich literature indicates that they have major effects on society. For instance, Bentzen (2019) provides evidence indicating that earthquakes promote religiosity while Belloc et al. (2016) associate them to a slower democratisation process.

[4]Michalopoulos and Xue (2019) show that modes of living of pre-modern people shaped the motifs that appear in their tales and mythology, with profound implications for growth, development and culture.

(2012)—, with only a few notable exceptions tracing the relationship back to the enlightenment period and before: Squicciarini and Voigtländer (2015) show that knowledge elite concentration raised productivity, Mokyr (2018) argues that intellectual competition facilitated the industrial revolution in Europe and Chen et al. (2020) discuss how the Chinese civil servant examination system locally promoted human capital accumulation. This contrasts with the wealth of evidence documenting alternative deep-rooted factors for development, notably agriculture, geography and climate (Ashraf and Galor (2011), Ashraf and Galor (2013), Alsan (2015), Cervellati et al. (2019) and Dalgaard et al. (2015)).[5] Our paper bridges the gap in the previous literature, connecting human capital and economic growth in the very long run. In doing so, it also relates to the research documenting factors that promote human capital accumulation, especially in pre-modern times. There is ample evidence for religion (Becker and Woessmann (2009), Valencia Caicedo (2018), Waldinger (2017)), the early introduction of the printing press (Baten and van Zanden (2008)) or institutional factors (Galor et al. (2009), Bobonis and Morrow (2014)). However, our paper focuses on a crucial prior stage: cognisance and human capital shaped early in history.

This paper is also related to the literature that analyses the effects of natural events on social organisation. Cavallo et al. (2013) show that natural disasters promote political revolutions, thereby affecting growth. Belloc et al. (2016) and Bentzen (2019) focus on earthquakes, finding a slowdown in the transition from autocracy to self-governance in mediaeval Italy and an increase in religiosity, respectively. By analysing the effects of solar eclipses, which are harmless phenomena, we depart from this literature. The distinction is important as we are interested in human curiosity: destructive events may divert thinkers' interest away from explaining the phenomena towards more urgent reconstruction and kill them. Similarly, physical capital losses retard economic growth, eroding the need for more complex social organisations.

The remainder of the paper is as follows: Section 2 discusses the mechanism we postulate. Section 3 presents the data and empirical strategy. The benchmark results are reported in Section 4, including a series of robustness tests in Section 5. We explore the empirical validity of our mechanism in Section 6. Lastly, Section 7 concludes.

[5] Furthermore, cultural traits important for growth —time preference, individualism, cooperation and cultural transmission— are ultimately shaped by these same factors: Galor and Özak (2016), Vollrath (2011), Litina (2016) and Giuliano and Nunn (2017).

2 Solar Eclipses, Curiosity and Human Capital

During a solar eclipse, the Moon blocks sunlight, shadowing parts of the Earth. Additionally, the temperature drops —up to 10 degrees— and wind slows down and changes direction.[6] With sunlight being essential for life, the disappearance of the Sun from the sky was a dreadful event that shocked pre-modern societies.[7] However, it also prompted thinking: Iwaniszewski (2014, p. 288) argues that humans always tried to unravel the mysteries of the sky and Barale (2014, p. 1763-1766) indicates that eclipses were a cause of curiosity (and fear), together with many other rare atmospheric phenomena. Indeed, although eclipse forecasting is an elusive task —especially for solar eclipses—, several people achieved surprising success, attesting their intellectual effort to comprehend them.[8]

Attempts to rationalise inexplicable natural phenomena by pre-modern societies gave origin to evolving explanations that eventually fossilised as folklore and mythology.[9] The original beliefs mutated when old explanations became unsatisfactory, and Ludwin et al. (2007) describes this process as "early attempts at scientific explanation" that require intellectual effort. The scope for re-examining and improving an explanation increases as its triggering event recurs, fueled by the "human nature [that] demands an explanation for events". This was the case in Japan, where a yin-yang-based theory for the origin of earthquakes superseded an older one that relied on gods, as the latter was deemed "an unsophisticated theory" (Ludwin et al. (2007)).

Indigenous endeavours to elucidate the causes of solar eclipses have similarly entered folklore. As earthquake "knowledge" advanced in Japan, so did the understanding of solar eclipses. These reflect varying levels of comprehension, probably revealing a deeper reflection on its causes.[10] The simplest explanation attributes the disappearance of the Sun to animals or gods: they either eat it or steal it. The Cherokee and Vietnamese believed that a giant frog ate the Sun,

[6] Gray and Harrison (2012) and Eugster et al. (2017).

[7] All sorts of nefarious consequences occurred during a solar eclipse: poisonous midsts descended onto Earth, a belief shared by German and Eskimo tribes; mediaeval French maintained that evil spirits roamed freely during the darkening of the Sun; and Hindu people followed protective rituals, see Littmann et al. (1999, p. 44–45).

[8] Some of them are summarised in Littmann et al. (1999, Ch. 4). Recorded eclipses also reflect interest in the phenomena, with Chinese recordkeeping stretching as far as 2043BCE, see Pankenier (2014, p. 2044, 2073–2074) and Kelley and Milone (2011, p. 118). Other people also kept records: the Zapotec (Justeson (2014, p. 765)) and Swedes (Ruggles (2014, p. 357)).

[9] For instance, self-ignited, ever-burning natural gas emissions that naturally occur in Yanartaş (Turkey) entered the oral tradition as the remains of the Chimera's flaming tongue (Piccardi and Masse (2007, p. vii)). In that sense, oral traditions contain the corpus of knowledge and "condensate and present information in a format that could be remembered and retold for generations" (Ludwin et al. (2007)). Several examples show folklore's longevity: the Klamath and the Gunditjmar mythology have kept records of volcanic eruptions that occurred 7700 and 37000 years ago (Matchan et al. (2020)).

[10] Hayden and Villeneuve (2011) argue that rival factions' competition over the precise date of the winter solstice advanced astronomical monitoring and knowledge of the skies.

a celestial dragon does so in China. Mythical dogs steal the Sun in Korea and, according to the Pomo in California, an angry bear is responsible. Other ethnic groups cleverly introduced the Moon, which reveals more careful observations on their part: for the Batammaliba, the Sun and the Moon clash and the only way to stop them from fighting is to halt all conflict on Earth. The Diné, the Wirangu and the Warlpiri explained that during an eclipse, the Sun and Moon are mating. Lastly, according to Littmann et al. (1999, p. 43), Armenian and Hindu myths maintain that dark bodies orbiting the Sun occasionally block the view of the Sun or the Moon, causing a corresponding eclipse. This is a fairly precise theory involving the actual mechanics of a solar eclipse: a celestial body casting its shadow on the Earth.

In line with Smith (1822, p. 21), we argue that, among pre-industrial ethnic groups, solar eclipses presented an intellectual challenge worth pondering upon. Additionally, the increasing levels of curiosity facilitated by more frequent eclipses "renders them [people] [...] more desirous to know [...]". Thus, cognitive development should correlate with frequency since "[w]onder [...] is the first principle which prompts mankind to the study [...]" (Smith (1822, p. 22)). For example, Dvorak (2017) proposes that a series of five solar eclipses in only twelve years prompted the Maya to begin recording them. Similarly, Liller (2000, p. 112) documents that the Rapanui started carving the Moai statues shortly after a series of five solar eclipses in ten years, followed by a sixth one and the passage of a comet sixty-five years later. Mokyr (2004, p. 15-16) discusses that knowledge arises from curiosity: "an essential human trait without which no historical theory of useful knowledge makes sense". Further, curiosity has moved the frontier of "propositional knowledge" (p. 287).

Besides a direct boost to human capital, indirect avenues may exist as well. Simple attempts at eclipse prediction require keeping a tally of, at least, 177–178 lunar months —see Dvorak (2017, Ch. 2), for instance. As such, a greater command of basic mathematics is required, and the development of written language can facilitate the task even more by allowing accurate recordkeeping. Moreover, a more careful sky observation may uncover additional regularities, useful to accurately establish the seasons or devise a calendar. Also, crafting precision instruments to track celestial bodies may present positive externalities through increased dexterity. Lastly, eclipses as well as other major events served as mnemonics of the local history and social rules. This was the case among some Plains tribes (Chamberlain (2000, p. 288) and McKnight (2005, p. XXII)).

Other natural phenomena share important similarities with eclipses. For instance, earthquakes, volcanic eruptions and tsunamis imply sudden changes in the surrounding landscape. In this sense, they equally qualify as triggers of curiosity and could contribute to human capital formation. However, most of these events are catastrophic and destructive, devastate communities and alter access to natural resources. Less severe cases may involve mass relocation of people to new lands. These economic setbacks delay growth. Alternative celestial events, such as supernovae and the passage of comets, present other drawbacks, too. First, their rather low frequency complicates group recalling. As mentioned earlier, human capital development implies the revision of older theories, and events separated by several centuries make this more difficult.[11] Lastly, from a practical perspective, these events are visible throughout the Earth and therefore equally affect all ethnic groups.

3 Data and Empirical Strategy

3.1 Data

This paper advances the hypothesis that more frequent exposure to total solar eclipses is related to higher economic development. We further propose one possible mechanism: human capital accumulation as ethnic groups make intellectual efforts to comprehend the phenomenon.[12] We rely on Murdock (1967) and Murdock and White's (1969) Ethnographic Atlas to obtain variables reflecting these outcomes. The Atlas contains a set of pre-modern societies when surveyed. These societies are, by construction, sparsely distributed across space, which reduces spatial correlation concerns. For these social groups, most of them not having mastered astronomy, solar eclipses would still represent a meaningful event worth explaining. Following Diamond (2017), we propose several standard variables that capture economic advancement. However, proxies for human capital or, similarly, complex thinking, are scarce. Nonetheless, we suggest that codifying a language in a written form and the playing of strategy games are related to human capital. Similar to Michalopoulos and Xue (2019), we use folklore data to study the explanations people ascribed to solar eclipses, which reflects their comprehension of the phenomenon and

[11]For comparison, the average time between total solar eclipses at the ethnic group level is 65 years.

[12]We remark, though, that we are interested in the intellectual effort these events represent while remaining agnostic regarding whether a conceived explanation is correct. In this sense, we see these events as forcing individuals to think about the unknown. Hence, even if the final explanation is clearly incorrect as of today standards —or even in comparison to similarly advanced societies— its ideation should increase cognitive skills.

human capital.[13] Data on total solar eclipses come from Espenak and Meeus (2006) and includes information about all total solar eclipses that occurred between the years 2000BCE and 2000CE. In what follows, we describe our main variables of interest.

Economic development. According to Diamond (2017), societal complexity is a prominent feature of developed ethnic groups. Moreover, starting from Murdock and Provost (1973), anthropologists have systematically argued that these proxies of social organization indicate cultural complexity. The Ethnographic Atlas provides three variables directly related to ethnic groups' social organisation. The first variable conveys information about the levels of hierarchy that exist beyond the local community. Five levels are possible, and more hierarchical societies score higher in this indicator. The second variable measures political integration. In this case, the indicator presents six differentiated categories: absence of local integration, autonomous local communities, peace groups transcending local communities, minimal states, little states and states. Lastly, we focus on class stratification among freemen within ethnic groups. There may be no distinction among freemen, or alternatively, individuals may belong to social classes determined by wealth, elite status, dual classifications or more complex systems.

We augment the set of outcomes using the Standard Cross-Cultural Sample, which provides more ethnic information for a selected group of ethnicities. Among the variables presented, we further proxy economic development by focusing on technological achievement and population density. We follow the technological advancement index of Eff and Maiti (2013) for the societies in the SCCS.[14] Lastly, population density follows Pryor (1985): less than one person per square mile, between one and five, five and 25, 25 and 100, 100 and 500 or more than 500 people per square mile.

Human capital. The Ethnographic Atlas does not record any variable directly related to human capital. However, it is possible to find proxy indicators that reflect deeper and more intricate reasoning. First, we focus on the existence of a written language. In its original form, writing progression indicates whether a group has no writing, uses mnemonic devices, has nonwritten records, has mastered writing but has no records or, finally, has a true writing system with records. We transform this scale into a binary variable stating whether writing is present –last two categories– or not.

[13] We use the same source for folkloric data as Michalopoulos and Xue (2019), retrieved from Nikolaev et al. (2015).

[14] The gist of this classification is that it considers that some tasks are predecessors of others, thus tasks that have more predecessors represent a more technologically advanced activity.

Our second proxy variable informs us about the types of games played in the society. These can be physical games, chance games, strategy games or a combination of the previous. We transform this variable into a dummy indicator stating whether an ethnic group plays strategy games or not. Strategic behaviour is indicative of advanced cognitive skills —Zern (1979) and Spitz (1978)— and societies that rely on strategic thinking develop such games to teach the next generations how to operationalise it.

Lastly, we use data on folklore from Berezkin in a way akin to Michalopoulos and Xue (2019). We focus on how solar eclipses enter into oral tradition. In particular, we are interested in discerning whether the Moon and Sun play a role in explaining solar eclipses. In that sense, as described before, some ethnic groups attribute eclipses to demons and animals eating or scaring the Sun. We expect more complex explanations involving the Moon to ensue from greater exposition to eclipses.

Solar Eclipses. To capture the long-lasting impact of solar eclipses, we construct a novel dataset of their incidence at the ethnic-group level, bringing together a wide range of historical, ethnic and GIS data sources. Among the different types of eclipses, we focus on total and annular eclipses. In these two sorts, the Moon completely obscures the Sun, effectively turning day into night. The most comprehensive dataset about solar eclipses is Espenak and Meeus (2006), which compiles all the relevant information for all solar eclipses occurring between 2000BCE and 3000CE. Based on this data, Jubier (2019) computes "paths of totality" for each eclipse: all positions on Earth from which a total solar eclipse is visible. In fact, total solar eclipses are visible only within a relatively narrow area, typically not wider than 160 km.[15]

Our main independent variable is the number of total solar eclipses visible from within each ethnic homeland. We construct it by intersecting eclipse paths with ethnic homeland boundaries from Fenske (2014). We restrict the data to eclipses that took place between the years 2000BCE and 1500CE. Figure 1 presents several paths of totality[16] and exemplifies the construction of our independent variable.

We argue that solar eclipses present several advantages compared to other natural phenomena. First, their occurrence is rare. Individuals can become accustomed to more common events, for instance, lightning. We thus believe that solar eclipses are more likely to have a long-lasting impact. Second, unlike earthquakes and volcanic eruptions, solar eclipses do not destroy physical

[15]This area appears naturally as the shadow the Moon casts transverses the Earth due to the movement of both bodies.

[16]We draw the reader's attention to their narrow and elongated shape.

or human capital. Capital destruction would directly affect complex thinking and societies beyond the cognitive channel we postulate. Lastly, solar eclipses are well distributed across the Earth and the effects can be perceived by a large collectivity.

Table 15 in the Appendix indicates the average number of eclipses that have ever been visible in a homeland, which is around 70, while Figure 2 depicts the number of solar eclipses at the ethnic level. This number is large because we use the number of eclipses visible over the course of 3500 years. By doing so, we capture the actual frequency of eclipses better than if we used narrower time frames more prone to idiosyncratic variation.[17]

Other Controls. The Ethnographic Atlas provides several control variables at the ethnic-group level. Our benchmark specification includes agricultural intensity. We augment it by accounting for habitat characteristics.

Furthermore, we rely on GIS solutions to compute additional variables related to economic development. First, we introduce a series of standard climatic and geographic controls: average temperature and precipitation, climate typology, absolute latitude and a south dummy.[18] Following Nunn and Puga (2012), we include controls for terrain ruggedness and elevation.

We also introduce the distance to the coast and distance to the rivers because early civilizations and early state formation took place near waterways as Mann (2012) indicates. Additionally, exposure to foreign ideas is higher near major communication hubs: ports in pre-modern times. Similarly, we follow Ashraf and Galor (2013) and we control for the terrestrial distance to Addis Ababa to capture the effect of genetic diversity. We further include measures for malaria prevalence and potential caloric yield. The mortality burden posed by malaria can negatively affect the adoption of new technologies —as malaria prevalence can induce inbreeding and high mortality rates can deter technological progress through a shortened life expectancy. According to Galor and Özak (2016) and Diamond (2017), higher potential caloric yield can both directly and indirectly —through preferences— foster economic development.

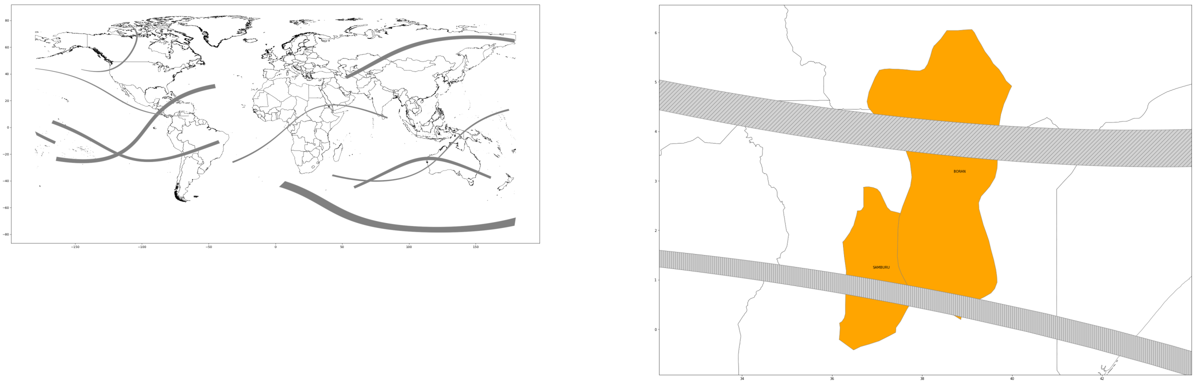
In the robustness and discussion Sections, we further augment the analysis with an additional set of geographical controls including the area of each ethnic homeland (larger areas are exposed to more eclipses), dependency on different modes of production and ecological diversity. Further, we also show that our results are robust to other dreadful events: volcano eruptions and earthquakes. Moreover, neither lunar eclipses nor cloud coverage affects our results.

[17] Our results, though, are robust to the introduction of alternative, shorter time frames of 500 years from different epochs.

[18] Because of the tilted Earth axis, the northern hemisphere experiences more solar eclipses.

Figure 1: Paths of totality.

(a) Global coverage. (b) Eclipses at the ethnic homeland level.



Notes: Figure 1a represents several paths of totality for selected total solar eclipses. Each path of totality covers a narrow area no wider than 160 km that stretches in the east-west direction. Figure 1b displays several ethnic homelands together with some selected paths of totality. Our main variable, the number of total solar eclipses visible from within an ethnic homeland, is obtained by counting the number of paths of totality that intersect a given ethnic homeland.

Table 15 in the Appendix reports the summary statistics for all our dependent and explanatory variables as well as for the ethnic and geographical controls. The data are all reported at the level of our unit of analysis: the ethnic group.

3.2 Empirical Strategy

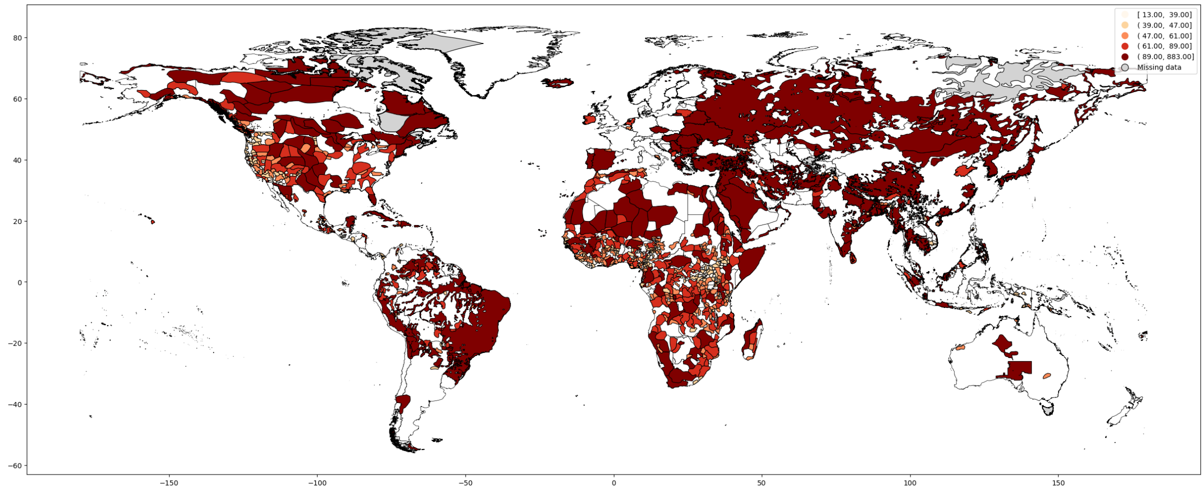
Using the aforementioned data we estimate the following equation:

$$C_i = \alpha_0 + \alpha_1 E_i + \alpha_2 \mathbf{I}_i + \alpha_3 \mathbf{G}_i + \alpha_4 \mathbf{D} + \varepsilon_i$$

where C_i denotes each of the six measures of economic development. E_i measures the number of eclipses an ethnic homeland has been exposed to. $\mathbf{I}_i$ and $\mathbf{G}_i$ are vectors of ethnic and geographical controls, respectively. $\mathbf{D}_i$ denotes continent fixed effects capturing unobservables across continents in which ethnic groups are located, and ε_i is an ethnicity-specific error term. We cluster standard errors at the regional level.

All our dependent variables, except for writing and technology levels, are ordered. Therefore, most regressions follow an ordered logit model and, for these variables, we use OLS. Our results report the obtained coefficients as well as the marginal effects.

Figure 2: Distribution of total solar eclipses at the ethnic homeland level.



Notes: This Figure represents the number of total solar eclipses that occurred between the years 2000BCE and 2000CE that were visible from within ethnic homeland boundaries.

4 Empirical Findings

This section reports the results of our benchmark analysis, relating the prevalence of total solar eclipses to economic development. We relegate the discussion of human capital as a possible mechanism to Section 6. First, we present the results from the Ethnographic Atlas and, later, we focus on the SCCS.

Ethnographic Atlas Outcomes. Table 1 explores the relationship between a higher exposition to total solar eclipses and economic development, when, following Diamond (2017), we proxy the latter by social complexity. Columns (1)–(3) focus on *Jurisdictional Hierarchy*. Column (1) reports the coefficient when we control only for continental fixed effects. Column (2) augments the analysis with all the relevant geographical controls while column (3) enriches it with the addition of the ethnic-group controls. In a similar fashion, Columns (3)– (6) and (7)–(9) report the results for *Political Integration* and for *Class Stratification*, correspondingly.

As Columns (1), (4) and (7) establish, there exists a positive and significant relationship between a higher incidence of total solar eclipses and economic development. Furthermore, adding additional controls for geographical and ethnic-group characteristics renders the results slightly stronger without affecting the significance.[19] In all cases, our findings are qualitatively

[19] In the rest of the paper, we will always refer to the specifications employed in Columns (3), (6) and (9) as the benchmark specification. This specification has the full set of basic controls that, on the one hand, captures a wide range of confounding factors and, on the other hand, maximizes the number of observations. Later, the benchmark specification is the starting point when conducting our robustness checks and when testing competing theories and other potential confounding factors.

Table 1: Benchmark results: EA — Solar eclipses and economic development.

	Jurisdictional Hierarchy			Political Integration			Class Stratification		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Total number of eclipses	0.014***	0.015***	0.008***	0.011***	0.012***	0.011**	0.008***	0.013***	0.008***
	(0.003)	(0.003)	(0.002)	(0.003)	(0.004)	(0.004)	(0.003)	(0.003)	(0.003)
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geography	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Ethnic	No	No	Yes	No	No	Yes	No	No	Yes
Pseudo-R^2	0.138	0.212	0.262	0.073	0.180	0.259	0.075	0.144	0.179
Observations	1111	911	911	307	255	255	1067	825	825

Notes: This Table presents the results of ordered logit regressions relating the impact of eclipses on the measures of societal complexity, as a proxy for economic development, at the ethnic-group level. Columns (1)–(3) report the findings for the *Jurisdictional Hierarchy* variable. Columns (3)–(6) and (7)–(9) report the results for *Political Integration* and for *Class Stratification*, respectively. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

significant at the one per cent level and quantitatively similar and stable across specifications even after the introduction of the full set of controls. In particular, as Table 2 reveals, increasing the average number of total solar eclipses per century by one raises the probability of reaching the top echelons of each of the outcomes by 0.6, 3.3 and 1.8 percentage points, respectively.[20] The average number of solar eclipses per century is about 1.73, with a standard deviation of 1.36.[21] In that sense, the marginal effects we discussed above correspond to a relatively mild rise in the number of eclipses. However, the effects are sizable. We measure a 0.6 percentage points increase in the probability of reaching the highest level of jurisdictional hierarchy when only 2.31% of the groups in the sample are located in that echelon. Comparatively, the relative increase in the probability of having a full-fledged state raises by 3.3%, with 13.73% of the ethnic groups in that category. Lastly, the likelihood of having a complex class stratification is 2.2 percentage points larger, compared to 7.76% of the groups in that level of class stratification.

Table 2: Marginal effects: EA — Economic development.

Jurisdictional Hierarchy		Political Integration		Class Stratification	
No levels	-0.046^{***}	Absent	-0.019^{**}	Absent	-0.057^{***}
	(0.013)		(0.009)		(0.019)
1 level	0.004^{**}	Local com.	-0.038^{**}	Wealth	0.005^{**}
	(0.002)		(0.015)		(0.003)
2 levels	0.020^{***}	Peace groups	-0.001	Elite	0.003^{**}
	(0.006)		(0.001)		(0.001)
3 levels	0.016^{***}	Min. states	0.008	Dual	0.031^{***}
	(0.004)		(0.006)		(0.011)
4 levels	0.006^{***}	Little states	0.016^{**}	Complex	0.018^{***}
	(0.002)		(0.007)		(0.006)
		States	0.033^{**}		
			(0.014)		

Notes: This table presents the marginal effects of the results reported in Table 1 for the three measures of social complexity. The full set of controls is considered in the analysis. Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

SCCS Outcomes. In order to further validate the previous findings, we now turn to a richer sub-sample: the Standard Cross-Cultural Sample. It covers about 186 ethnic groups but offers a wider range of variables. Among these, we select three that convey a clear sense of

[20] The average number of eclipses per century equals the total number of eclipses divided by 40.

[21] The sample changes between specifications. The average value and the standard deviation of the number of eclipses per century are 1.75 and 1.44 when the outcome is Jurisdictional Hierarchy; 2 and 1.40 for Political Integration; and 1.77 and 1.48 for Class Stratification. We have previously reported the overall average and standard deviation.

Table 3: Benchmark results: SCCS — Solar eclipses and economic development.

	Technological Level			Population Density		
	(1)	(2)	(3)	(4)	(5)	(6)
Total number of eclipses	0.003* (0.002)	0.004*** (0.001)	0.004** (0.002)	0.002 (0.002)	0.004 (0.003)	0.016*** (0.006)
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Geography	No	Yes	Yes	No	Yes	Yes
Ethnic	No	No	Yes	No	No	Yes
Pseudo-R^2	0.345	0.577	0.706	0.090	0.276	0.454
Observations	129	108	108	166	139	139

Notes: This Table presents the results of regressions relating the impact of eclipses on the measures of economic development, at the ethnic-group level. Columns (1)–(3) report the findings for the *Technological Level* variable and follow an OLS regression. Columns (3)–(6) report the results for *Population Density* using ordered logit regressions. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.$^{*}\, p < 0.1$, $^{**}\, p < 0.05$, $^{***}\, p < 0.01$.

economic development: the technological level reached by each group, and population density.[22] Regressions related to technological level follow OLS, while we use ordered logit regressions when the outcome variable is population density.

We report the results for the SCCS on Table 3. Columns (1)–(3) focus on the *Technological Level* and, in the remaining, the outcome variable is *Population Density.* As in Table 1, we first control only using fixed effects, which we then augment incorporating geographical variables and finally ethnic-group characteristics.

The results under these alternative specifications also indicate a positive and significant relationship between solar eclipse intensity and economic development that is consistent with the previous set of outcomes. In that sense, we have multiple pieces of evidence suggesting that ethnic groups located in places that experience more solar eclipses are more developed. We postpone for the moment the discussion of the mechanism we propose, namely, that these societies are more challenged by unexplained phenomena which prompts them to think more, thereby raising their human capital levels. Because most of the outcomes are obtained under ordered logit regressions, the magnitude of the effects is better interpreted in marginal terms, as displayed in Table 4. In this case, the average number of eclipses per century is about 2.18 and

[22]The technological level is not directly present in the SCCS database but Eff and Maiti (2013) provide values for this sample.

the standard deviation is about 2.10, slightly larger than when using the EA sample.[23] Table 4 reports the marginal effect of a one-unit change in the incidence of eclipses, this is, of one additional eclipse per century, for each of the outcomes. In that sense, we measure an increase in the technological level of 0.175 units, out of a mean of 9.45. The effect is even larger for population density: an additional eclipse per century increases the likelihood of being in the densest category by 1.4 percentage points, while only 3.6% of the ethnic groups in the sample are in this echelon.

Overall, our analysis indicates a systematic effect of the incidence of eclipses on economic development. The magnitude of our results is not trivial, especially taking into account that we consider eclipses over such a long period. In the following section, we test the robustness of our benchmark findings to a series of alternative assumptions and additional controls.

Table 4: Marginal effects: SCCS — Economic development.

Technological Level	Population Density	
0.175^{**}	Less than 1 / sq. mile	-0.040^{***}
(0.070)		(0.014)
	1-5 / sq. mile	-0.008
		(0.006)
	5-25 / sq. mile	-0.005
		(0.005)
	25-100 / sq. mile	0.016^{***}
		(0.004)
	100-500 /sq. mile	0.024^{**}
		(0.011)
	500 or more / sq. mile	0.014^{***}
		(0.005)

Notes: This table presents the marginal effects of the results reported in Table 3 for the three measures of economic development. The full set of controls is considered in the analysis. Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5 Robustness

Validity of the eclipse measure. Our measure of eclipses, and in particular the choice of the time period, is quite broad to capture the average incidence of solar eclipses. Yet, for consistency, we explore alternative, shorter time horizons to dispel concerns regarding our

[23]The corresponding average and standard deviation for the regressions employing Technological Level and Population Density as outcomes are 2.02 and 2.25; and 2.32 and 2.34, respectively.

baseline timing. Figure 3 report the results for all six measures of economic development when using alternative periods to compute the total number of eclipses. These measures consider the following periods: 2000BCE-1500BCE, 1500BCE-1000BCE, 1000BCE-500BCE, 500BCE-0CE, 0CE-500CE, 500CE-1000CE and 1000CE-1500CE.[24]

Alternative eclipse measures. While we argue that an eclipse is an impressive event which may have a long-lasting impact on people, we highlight that an additional feature of eclipses that reinforces their impact is their rather low frequency. Table 5 incorporates three different measures of frequency: the average time between two consecutive eclipses in Panel (A), the minimum time between consecutive eclipses in Panel (B) and the maximum time between consecutive eclipses in Panel (C). The results of this exercise are in line with our hypothesis, this is, more frequent eclipses are associated with higher development, except for the minimum time between consecutive eclipses.[25] However, we believe the total number of eclipses to be a more straightforward and easy to interpret measure, hence our preference for it. At any rate, however, the total number of eclipses already embodies a frequency component: the average time between eclipses.[26] At any rate, though, all measures are highly correlated.

Additional ethnic controls. Our benchmark analysis controls for a wide range of ethnic and geographical controls as well as various fixed effects. To further mitigate concerns about possible omitted variables, Figure 4 augments the benchmark analysis with a series of additional ethnic-group controls.[27]

In general, the inclusion of additional controls, either one by one or all together, does not change the main result, namely, that an increase in the number of total solar eclipses positively affects economic development, with the exception of population density measures. In that sense, the previous results are not caused by omitted variables related to production modes.

Other rare events. Next, we investigate to what extent other rare events may have influenced our outcomes of interest. After all, our hypothesis hinges on the fact that such episodes trigger curiosity, positively contributing to human capital formation. We know with certainty that several other types of rare events occurred over the course of thousands of years

[24]Table 16 in the Appendix presents the regression results.

[25]This lack of results is hardly surprising, though: decreasing the minimum does not produce much additional surprise since its average value is two years between consecutive eclipses.

[26]The average time between eclipses equals 3500 divided by the number of eclipses. Note, though, that the alternative measures we propose are more finely grained: they consider the time between consecutive eclipses. Dvorak (2017) and Liller (2000, p. 112) implicitly suggest the number of eclipses in short succession as an alternative metric.

[27]Table 17 in the Appendix documents the results of the corresponding regressions, displaying the coefficient of each additional variable.

Figure 3: Robustness: Alternative time frames.

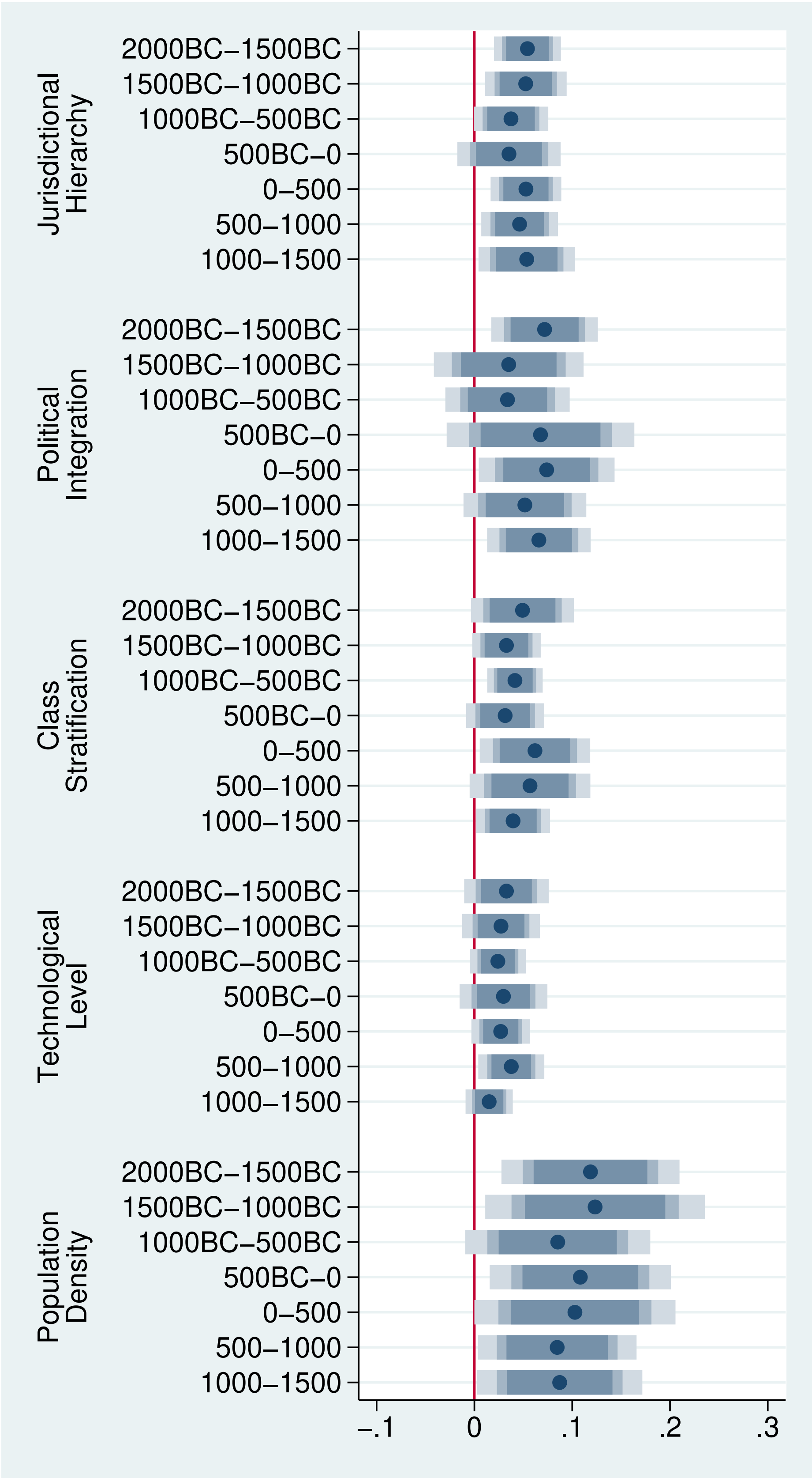
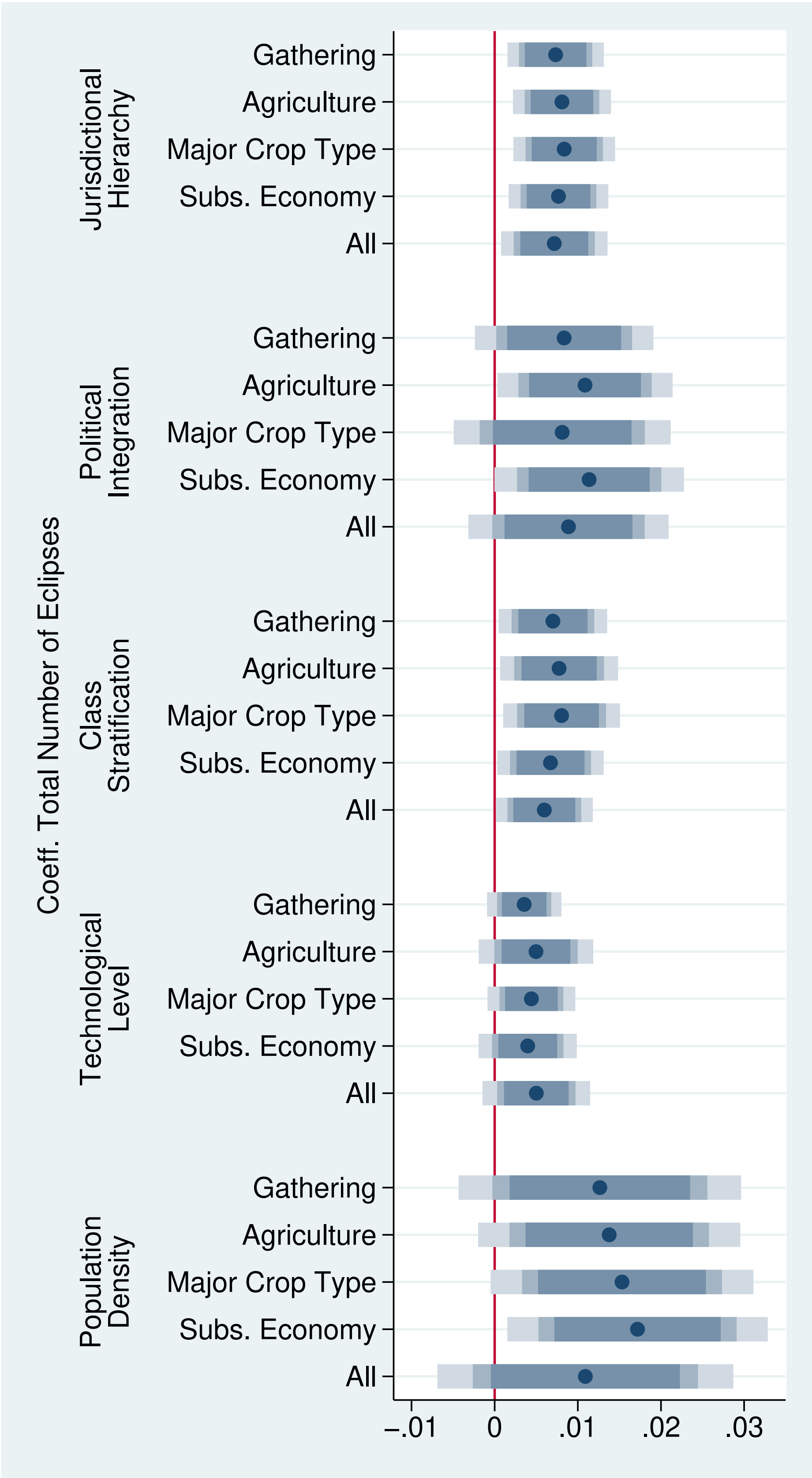


Table 5: Robustness: Alternative measures of eclipse incidence.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
			A: Avg. Time		
Avg. time between eclipses	−0.830	−0.887**	−1.174***	−1.593**	−6.506***
	(0.530)	(0.415)	(0.420)	(0.720)	(2.136)
Pseudo-R^2	0.255	0.253	0.175	0.713	0.463
Observations	911	255	825	108	139
			B: Minimum Time		
Minimum time between eclipses	1.592	8.391	−0.611	−2.700	−10.141
	(4.016)	(8.775)	(4.496)	(4.731)	(11.931)
Pseudo-R^2	0.255	0.254	0.172	0.694	0.428
Observations	911	255	825	108	139
			C: Maximum Time		
Maximum time between eclipses	−0.191*	−0.069	−0.201**	−0.458***	−0.482
	(0.100)	(0.230)	(0.099)	(0.146)	(0.539)
Pseudo-R^2	0.256	0.252	0.175	0.745	0.432
Observations	911	255	825	108	139
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: This table reports the results of regressions including alternative measures of eclipse frequency as an independent variable. Panel (A) includes in the analysis the average time between consecutive eclipses, Panel (B) the minimum time and Panel (C) the maximum time between two consecutive eclipses. Dependent variables measured in centuries. The full set of controls is considered in the robustness analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 4: Robustness: Additional ethnic controls.



and may as well have instilled fear or may have been catastrophic. When describing solar eclipses in Section 2, we listed several characteristics that make them unique: their rare occurrence, their non-destructive nature and the partial visibility. While all the above characteristics make eclipses a significant factor, we test additional events. In Table 6 we include three other types of rare events: volcanoes —proxied by the distance to the closest one— in Panel (A), distance to tectonic faults in Panel (B) and the incidence of lunar eclipses in Panel (C).

In all three cases, we find no significant effect of any of these events on our outcomes. The non-significance of lunar eclipses was expected. After all, lunar eclipses are less impressive as they are not accompanied by major changes in luminosity, temperature or animal behaviour. Moreover, they happen at nighttime and can go unnoticed by people, and are visible on a whole hemisphere at once, making them more frequent and less impressive. Distance to volcanoes and tectonic faults proxies the likelihood of observing volcanic eruptions and earthquakes —both catastrophic and destructive events that nonetheless can raise awareness about the unknown. Although eruptions and earthquakes, especially the largest of them, have vanished whole civilizations from Earth, ethnic groups far enough could have perceived them, contributing towards their levels of complexity of that society.[28] Additionally, EA outcomes using social complexity as a proxy for economic development remain positive and highly significant. However, the proxies derived from the Standard Cross-Cultural Sample become less significant once we control for lunar eclipses in the last Panel.[29]

Table 6: Discussion: Other rare events.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
	Panel A: Volcanoes				
Total number of eclipses	0.008^{***}	0.011^{**}	0.009^{***}	0.004^{**}	0.016^{***}
	(0.002)	(0.004)	(0.003)	(0.002)	(0.006)
Dist. Volcano	0.000	−0.000	-0.001^{**}	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
R^2 Pseudo-R^2	0.262	0.259	0.185	0.706	0.455

[28]Volcanic eruptions have entered the local mythology. For instance, the Klamath in America associated the volcanic eruption of Mount Mazama with godly affairs: Mount Mazama last erupted about 7700 years ago. According to Matchan et al. (2020), Australian Gunditjmara people kept a similar oral myth for even longer. Chester and Duncan (2007, p. 206) provides more examples.

[29]The lack of significance is likely caused by the high correlation displayed between solar and lunar eclipses in the Standard Cross-Cultural Sample: 0.93. This value is much lower when working with outcomes from the Ethnographic Atlas, reaching only 0.62.

Observations	911	255	825	108	139
	Panel B: Tectonic Faults				
Total number of eclipses	0.008***	0.011**	0.009***	0.004**	0.016***
	(0.002)	(0.004)	(0.003)	(0.002)	(0.006)
Dist. Tec. Fault	−0.000	−0.000	−0.000	0.000	−0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
R^2 Pseudo-R^2	0.262	0.260	0.181	0.708	0.460
Observations	911	255	825	108	139
	Panel C: Lunar Eclipses				
Total number of eclipses	0.007**	0.009	0.007**	0.007	0.017*
	(0.003)	(0.006)	(0.004)	(0.006)	(0.010)
Total number of lunar eclipses	0.001	0.002	0.001	−0.002	−0.001
	(0.001)	(0.003)	(0.001)	(0.005)	(0.008)
R^2 Pseudo-R^2	0.262	0.259	0.179	0.706	0.454
Observations	911	255	825	108	139
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: This table analyses the effects of three other types of rare events: volcanic eruptions, proxied by distance to volcanoes, in Panel (A), distance to tectonic faults in Panel (B) and the incidence of lunar eclipses Panel (C). The full set of controls is considered in the analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Lastly, we also test to what extent partial eclipses may have had a similar impact. Partial solar eclipses are visible in a much wider area than their total counterparts. However, the obscuration decreases rapidly as one moves farther away from the path of totality and, according to (Hughes, 2000), 90% of the Sun must be shadowed to perceive the implied decrease in luminosity. Therefore, we construct buffers of 50 and 100 km around each path of totality to account for the area likely to be in the penumbra of the eclipse, this is, to experience a partial eclipse. Table 7 incorporates the number of total and partial eclipses as regressors. Panel A presents the results for the 50 km buffer and Panel B extends it to 100 km. Mostly, only total eclipses predict economic development while partial eclipses do not seem to be important. Partial eclipses do not appear to be significant predictors of economic prosperity, even when considering a 100 km extension around total solar eclipses. In that sense, it is likely that the much-decreased obscuration associated with them explains our results, this is, at those distances, the drop in luminosity can be small and thus go unnoticed.

Table 7: Discussion: Partial eclipses.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
	Panel A: 50 km				
Total number of eclipses	0.008***	0.011***	0.008***	0.004**	0.016***
	(0.002)	(0.004)	(0.003)	(0.002)	(0.006)
Total number of partial eclipses	−0.008	−0.008	−0.010	0.028	−0.021
	(0.018)	(0.036)	(0.017)	(0.042)	(0.043)
R^2 Pseudo-R^2	0.262	0.259	0.179	0.710	0.454
Observations	911	255	825	108	139
	Panel B: 100 km				
Total number of eclipses	0.009***	0.010***	0.008***	0.004**	0.017***
	(0.003)	(0.004)	(0.003)	(0.002)	(0.006)
Total number of partial eclipses	−0.005	0.008	−0.002	0.015	−0.031
	(0.013)	(0.023)	(0.012)	(0.021)	(0.033)
R^2 Pseudo-R^2	0.262	0.259	0.179	0.708	0.456
Observations	911	255	825	108	139
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: This table incorporates partial solar eclipses as an additional regressor alongside the number of total solar eclipses. Partial eclipses computed at 50 and 100 km buffers in Panels A, and B, respectively. The full set of controls is considered in the analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.$^{*}\, p < 0.1$, $^{**}\, p < 0.05$, $^{***}\, p < 0.01$.

Spatial correlation. The number of total solar eclipses may be spatially correlated across ethnic groups, affecting the statistical significance of our results. In fact, the path of totality spans several thousand kilometres in an east-west direction, thus simultaneously affecting multiple ethnic groups located closeby. A first line of argument against this concern is related to the very construction of the data. Murdock's efforts to collect data in the Ethnographic Atlas were made with the intention of mitigating correlation across groups over space and time.[30]

We further try to empirically address this concern by conducting some additional tests in Table 8.[31] First, Panel (A) incorporates the number of eclipses visible from the closest neighbour's homeland as an additional regressor. This variable allows us to control for potential communication between groups, especially about eclipses, which would otherwise appear as noise. Panel (B) uses an alternative level to cluster the results: ecoregions. Besides being more precise, ethnic groups within the same ecoregion face similar difficulties from the habitat, for instance, in terms of food availability, soil characteristics or building materials. Lastly, Panel (C) exploits the fact that ethnic groups whose languages are siblings or closely related tend to display similar characteristics arising from a common, shared history. In that sense, we introduce language fixed effects as an additional control and cluster the standard errors at that same level. In general, these more demanding specifications do not challenge our previous association between eclipses and economic development.

A final concern is related to mass migrations of ethnic groups, particularly, the Bantu expansion that occurred between 1000BCE and 1CE.[32] It consisted of a series of sequential migrations, from western Africa to the east and south. In Table 9 we first exclude, in Panel (A), west, central, east and southern African regions from the regression. Panel (B) further expands the exclusion to the whole African continent. In general, the results are similar to those we obtained before.

Location accuracy and visibility. Two final concerns we address are related to the accuracy of the location of the eclipses as this would affect their visibility of eclipses from a particular location, as well as their visibility due to climatic conditions.

[30] In the literature, the possible correlation between cultures is known as Galton's problem. When collecting his data, Murdock sampled cultures as independently as possible to mitigate this concern (see e.g.Mace et al. (1994)).

[31] The obvious choice would be to compute Conley's standard errors. However, these are not available for ordered logit regressions.

[32] According to Giuliano and Nunn (2017), the Bantu expansion is the only migration that could have affected ethnic homeland boundaries. Therefore, we consider that all populations have been stable throughout time, except for the Bantu. Furthermore, our population predates the era of mass migration, hence there is no need to use a population matrix to reconstruct the original ethnic composition of any ethnic group.

Table 8: Robustness: Spatial correlation.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
	A: Nearest Neighbour				
Total number of eclipses	0.009***	0.010*	0.010***	0.006**	0.015**
	(0.002)	(0.006)	(0.004)	(0.002)	(0.006)
Eclipses neighbour	−0.002	0.001	−0.004	−0.011	0.003
	(0.002)	(0.003)	(0.003)	(0.006)	(0.004)
Pseudo-R^2	0.259	0.258	0.179	0.730	0.463
Observations	892	246	807	103	134
	B: Clustering at ecoregions				
Total number of eclipses	0.008***	0.011***	0.008***	0.004**	0.016***
	(0.002)	(0.004)	(0.003)	(0.002)	(0.006)
Pseudo-R^2	0.262	0.259	0.179	0.706	0.454
Observations	911	255	825	108	139
	C: Language Fixed Effects				
Total number of eclipses		0.021***	0.006***	0.016	−0.037
		(0.007)	(0.002)	(0.027)	(0.023)
Language FE		Yes	Yes	Yes	Yes
R^2 Pseudo-R^2		0.381	0.235	0.926	0.718
Observations		255	825	108	139
Controls (common to all regressions)					
Fixed effects		Yes	Yes	Yes	Yes
Geography		Yes	Yes	Yes	Yes
Ethnic		Yes	Yes	Yes	Yes

Notes: This table reports the results when we attempt to mitigate concerns about spatial correlation. Panel (A) controls for total eclipses visible in neighbouring ethnic homelands. Panel (B) clusters the standard errors at the ecoregion level. Panel (C) enriches the benchmark analysis with a set of language family fixed effects and clusters the standard errors at that same level. The full set of controls is considered in the robustness analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.$^{*}\,p < 0.1$, $^{**}\,p < 0.05$, $^{***}\,p < 0.01$.

Table 9: Robustness: Bantu expansion.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
	Panel A: Excluding Bantu Areas				
Total number of eclipses	0.007***	0.018***	0.010**	0.003*	0.025***
	(0.002)	(0.005)	(0.004)	(0.002)	(0.008)
R^2 Pseudo-R^2	0.363	0.351	0.261	0.743	0.529
Observations	530	191	507	91	110
	Panel B: Excluding Africa				
Total number of eclipses	0.006**	0.018***	0.011***	0.003*	0.027***
	(0.003)	(0.005)	(0.004)	(0.002)	(0.009)
R^2 Pseudo-R^2	0.373	0.351	0.290	0.705	0.557
Observations	477	180	463	88	104
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: This table reports the results when we attempt to mitigate concerns about mass migrations, in particular, the Bantu expansion. Panel (A) excludes the regions transversed by the Bantu: west, central, east and southern Africa. Panel (B) excludes the entire African continent. The full set of controls is considered in the robustness analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.$^{*}\,p < 0.1$, $^{**}\,p < 0.05$, $^{***}\,p < 0.01$.

First, our results may suffer from low accuracy regarding either homeland boundaries or eclipse paths. Although in general ethnic homeland boundaries are accepted as precise enough, this could nonetheless be an issue. Regarding eclipse paths, the exact local visibility hinges upon having precise estimates of the Earth's tidal frictions. Hence, the first eclipses in the series may be slightly mislocated. We address this double concern by shifting ethnic homelands three degrees northwards —alternative directions and amounts are equally valid. This effectively represents different ethnic boundaries and paths of totality. Panel (A) of Table 10 presents the results when we compute the total number of eclipses visible from the displaced ethnic homelands. The results remain qualitatively and quantitatively the same.

Second, we also address concerns regarding diminished visibility due to cloud coverage. In this case, we introduce average cloud coverage as an additional regressor. Although this variable is contemporaneous, we believe that global cloud patterns have not changed much over the course of centuries as these mostly result from winds and mountain ranges. Hence, even though cloud visibility is affected by micro-climatic conditions, the mean value should be roughly constant over time. The results of this second exercise, displayed in Panel (B) of Table 10, are also similar to the benchmark results. In fact, even if cloudy, during a total solar eclipse obscuration is above 90%, so the darkening of the sky would still be perceived.

Homeland area. The use of ethnic homelands as a basis to compute the number of total solar eclipses implies a mechanical relationship between each homeland's area and the latter. After all, we count all eclipses visible from *anywhere* within ethnic homeland boundaries, and a larger area implies that more eclipses are visible.[33] Since controlling a larger area may require more sophisticated forms of social organisation, Table 11 proposes several tests to mitigate this concern, although all regressions flexibly control for the area by introducing decile dummies. Panel (A) introduces ethnic homelands' area (in square-km) as control, replacing the area dummy indicators.[34]

Panels (B) and (C) propose an alternative method to disentangle the aforementioned mechanical relationship. First, we compute the number of eclipses within a fixed area for each ethnic group: 50 and 100 km radius around homeland centres. Second, we multiply it by

[33] Using the entire ethnic homeland as a basis has the advantage of encompassing information exchange between group members. This is, ethnic groups dispersed over large territories can communicate and exchange information on eclipses only seen by a fraction of the group.

[34] More developed ethnic groups may have expanded, occupying the territory and displacing previous settlers. In that sense, area would be an outcome of total solar eclipses, and hence it should not be a control. For this reason, the area is not part of the main set of independent variables.

Table 10: Robustness: Location accuracy and visibility.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
	A: Displaced Ethnic Homelands				
Total number of eclipses	0.009***	0.011**	0.008***	0.005**	0.016***
	(0.002)	(0.005)	(0.003)	(0.002)	(0.006)
Pseudo-R^2	0.262	0.259	0.178	0.707	0.454
Observations	911	255	825	108	139
	B: Cloud Coverage				
Total number of eclipses	0.008***	0.011**	0.008***	0.004**	0.016***
	(0.002)	(0.004)	(0.003)	(0.002)	(0.006)
Cloud coverage	0.000*	0.000	0.000*	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R^2 Pseudo-R^2	0.263	0.259	0.180	0.707	0.454
Observations	911	255	825	108	139
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: This table reports the results when we attempt to mitigate concerns about location accuracy and visibility In Panel (A) we create a new measure of eclipses by displacing ethnic homelands 3 degrees northwards and replicate the benchmark regression. In Panel (B) we account for actual eclipse visibility that might be affected by clouds. We control for the average level of cloud coverage over the year. The full set of controls is considered in the robustness analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.$^{*}\, p < 0.1$, $^{**}\, p < 0.05$, $^{***}\, p < 0.01$.

the actual area of each group. In doing so, our measure effectively proxies the expected number of eclipses within the homeland region, assuming that eclipses are homogeneously distributed. In other terms, we are purposely leaving aside idiosyncratic changes in the number of eclipses brought about by ethnic homelands' shape. Lastly, we regress our indicators of economic prosperity against both the expected number of eclipses and its actual counterpart.

Table 11: Discussion: Area.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
			Panel A: Area		
Total number	0.007**	0.005	0.007***	0.005	0.016**
of eclipses	(0.003)	(0.004)	(0.002)	(0.004)	(0.008)
Area	0.000	0.000***	0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R^2 Pseudo-R^2	0.257	0.257	0.176	0.694	0.419
Observations	943	269	856	113	145
			Panel B: Expected eclipses, 50 km radius		
Total number	0.007***	0.006	0.007***	0.005	0.016**
of eclipses	(0.003)	(0.004)	(0.003)	(0.004)	(0.007)
Expected eclipses	0.001	0.005**	0.000	−0.000	−0.000
50 km radius area	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)
R^2 Pseudo-R^2	0.257	0.256	0.176	0.694	0.419
Observations	943	269	856	113	145
			Panel C: Expected eclipses, 100 km radius		
Total number	0.007***	0.005	0.007***	0.005	0.016**
of eclipses	(0.003)	(0.004)	(0.003)	(0.004)	(0.007)
Expected eclipses	0.001	0.004***	0.000	−0.000	−0.000
100 km radius area	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
R^2 Pseudo-R^2	0.257	0.257	0.176	0.694	0.419
Observations	943	269	856	113	145
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: In this table we further address the fact that bigger homelands experience more eclipses. To mitigate this concern we directly control for the area in Panel (A). Panels (B) and (C) introduce the expected number of eclipses as additional regressors. The full set of controls is considered in the analysis, except for Panel (A) which does not include area decile dummies. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Overall, these strategies do not modify our previous conclusions. The results for economic development remain positive and highly significant throughout all the specifications. Additionally, as Panels (B) and (C) reveal, economic prosperity is not influenced by the expected number of eclipses, casting doubt on the premise that homeland areas drive the results. The lack of results for partial eclipses in Table 7 also point it that same direction. In fact, larger homelands experience more eclipses of *both* sorts. However, only total solar eclipses bear predictive power.

Other driving forces: scalar stress and ecological diversity. The literature on the formation of more complex societies, especially the empirical one, is not very extensive. A first hypothesis brought up is that of scalar stress (Johnson (1982)): societal stress that is reinforced by a growing population. The need to mitigate the concern associated with an enlarging population has led societies to more complex structures, which we may confound with economic advancement. Panel (A) of Table 12 controls for population density. Unfortunately, this variable is only available in the Standard Cross-Cultural Sample, hence the number of observations decreases. Our results remain intact. In particular, population density does directly affect any of the social complexity measures, nor technological development or writing.[35] Remarkably, though, the upper echelons of population density are related to social complexity (Columns (1)–(3)) but unrelated to the alternative measures of economic prosperity. This is in line with the theory of scalar stress.

Fenske (2014) proposes that ecological diversity has an effect on state centralisation. In particular, he shows that more ecologically diverse places are associated with more centralized states. His findings are based upon a sample of pre-colonial African ethnic groups, yet his insight is readily applicable to the full set of ethnic groups in Murdock's Ethnographic Atlas. In Panel (B) of Table 12 we directly take into account this theory by controlling for a measure of ecological diversity. The introduction of these additional controls renders the effect of total solar eclipses intact. Similarly to before, ecological diversity has a bearing on societal complexity, but it seems to be uncorrelated with alternative measures of prosperity, namely, technological advancement, writing and population density.

[35]For obvious reasons, we do not provide results for population density as an outcome.

Table 12: Discussion: Scalar stress and ecological diversity.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
	Panel A: Population Density				
Total number of eclipses	0.017*	0.040***	0.019**	0.002	
	(0.009)	(0.012)	(0.009)	(0.002)	
Pop. Density					
$<$ 1 p. / sq. mile	Ref.	Ref.	Ref.	Ref.	
1-5 p. / sq. mile	−1.091**	−0.807	0.104	0.502	
	(0.521)	(1.282)	(1.090)	(0.773)	
5-25 p. / sq. mile	2.980**	4.316***	1.510	0.309	
	(1.456)	(1.635)	(1.274)	(0.932)	
25-100 p. / sq. mile	2.739	3.650***	1.696	1.104	
	(1.706)	(1.395)	(1.241)	(0.943)	
100-500 p. / sq. mile	3.656*	4.629**	2.712**	0.803	
	(1.962)	(2.350)	(1.302)	(1.196)	
$>$ 500 p. / sq. mile	5.414***	5.208*	3.377	−0.142	
	(1.898)	(2.940)	(2.242)	(1.174)	
R^2 Pseudo-R^2	0.433	0.533	0.310	0.740	
Observations	139	100	139	98	
	Panel B: Ecological Diversity				
Total number of eclipses	0.008***	0.010**	0.008***	0.004*	0.016***
	(0.002)	(0.004)	(0.003)	(0.002)	(0.006)
Eco. diversity	0.580	0.731	0.932***	0.297	3.557**
	(0.374)	(0.717)	(0.304)	(0.740)	(1.690)
R^2 Pseudo-R^2	0.263	0.261	0.182	0.707	0.475
Observations	911	255	825	108	139
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: In this table we test whether scalar stress or ecological diversity are driving the results. In Panel (A) we account for scalar stress by controlling for population density. In Panel (B) we control for ecological diversity as suggested by Fenske (2014). Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.$^{*}\, p < 0.1$, $^{**}\, p < 0.05$, $^{***}\, p < 0.01$.

6 Mechanism

The previous Sections have established a clear and robust relationship between the number of total solar eclipses and economic development. In this Section, we explore one possible mechanism relating the two: increased levels of human capital. We argue that, by being more exposed to an unknown, rare and hard to explain phenomenon, people's curiosity is aroused, prompting thinking. In that sense, a higher incidence of solar eclipses would push its witnesses to think more as different generations experience eclipses. As we discussed in Section 2, the effects can be direct and indirect. Regarding the first, the disappearance of the Sun from the sky requires some immediate explanation, thus prompting thinking. Moreover, the observation of additional solar eclipses can help refine the initial interpretation for its causes, eventually realising about the role of the Moon. Indirect effects include the use of relatively large numbers and mathematical abstraction that are required for eclipse prediction. Also, a more careful observation of the skies can reveal patterns that help to create a more accurate calendar, for instance.

Unfortunately, neither the Ethnographic Atlas nor the SCCS provides us with direct measures of human capital. We circumvent this limitation by proposing variables that we believe indicate deeper and more complex thinking: the presence of a written language and the playing of strategy games. We argue that complex thinking is a natural predecessor of human capital. Moreover, we additionally rely on folklore data collected by Berezkin to assess whether ethnic groups located in eclipse-prone regions incorporate the Moon when explaining the causes of the phenomenon. In that sense, we test whether exposition to solar eclipses contributed to increasing ethnic groups' astronomical knowledge.

Writing is a binary indicator that displays different values reflecting whether a group has mastered writing.[36] In that sense, we see progress on this scale as indicating more complex thinking and, hence, contributing to human capital. Our second variable tracks whether strategy games are played, in contrast with the playing of only chance or physical games. Strategic behaviour is indicative of advanced cognitive skills and societies that rely on strategic thinking develop such games to teach the next generations how to operationalise it. This idea is in line with Zern (1979) and Spitz (1978), who suggest strategy games as an indicator of the

[36]The data proposes different levels that we collapse into two: no writing, mnemonic devices and non-written records are considered as indicating lack of written language. Evidence of writing, even if there are no records, is coded as demonstrating the existence of a written language.

development of cognitive abilities. Lastly, ethnic groups' explanation for eclipses reflects their understanding of this natural phenomenon.

Table 13 reports the effect of solar eclipses on our proxies for human capital. Columns (1)–(3) present the findings for *Writing*, Columns (4)–(6) report the results for the *Strategy Games* and Columns (7)–(9) focus on *Eclipse Explanation*. Column organisation mimics Table 1.

The outcome of the regressions indicates a positive association between the number of solar eclipses and the different proxies for human capital.[37] These results lend credence to the mechanism we propose. In particular, it is possible that attempts to understand solar eclipses have contributed positively to the accumulation of human capital, either directly —although the knowledge is not particularly useful by itself— or indirectly through the exercise of thinking and the discussion of theories with other people, which requires the use of logical arguments. As mentioned before, positive externalities may have also crystalised as additional human capital: the discovery of other celestial phenomena, which may be useful in navigation or the understanding of the seasons, the development of tools, etc. Lastly, increased levels of human capital would allow ethnic groups to reach higher stages of economic development.

As before, the results suggest that societies that experienced an additional eclipse per century are more likely to have a more complex writing system. In particular, the probability of having a written language increases by 16.5 percentage points. Likewise, ethnic groups are 6.2 percentage points more likely to play games of strategy, when the sample average is 20.54%. Lastly, we measure a 1.3 percentage points increase in the probability that the folkloric interpretation of eclipses includes the Moon and the Sun, revealing a deeper understanding of the phenomenon.

7 Conclusion

This paper revisits the importance of human capital for economic growth in a new setup: pre-modern societies that have not yet mastered science. Departing from classic explanations, we propose that rare, unexplained events trigger human curiosity, a natural precursor to human capital. In turn, higher levels of human capital would enable faster economic growth, reflected, according to Diamond (2017), in societal complexity.

We focus on a unique case of rare and frightening effect whose effects are felt by large collectivities: total solar eclipses. Total solar eclipses present three main characteristics that

[37] Robustness tests, not reported here but akin to those performed in Section 5 and available from the authors upon request, indicate that, for all variables, the association generally remains under more demanding conditions.

Table 13: Benchmark results: Mechanism — Solar eclipses and human capital.

	Writing			Strategy Games			Eclipse Explanation		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Total number of eclipses	0.003***	0.003***	0.004**	0.001***	0.001***	0.002***	0.001	0.002*	0.004**
	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.002)
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geography	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Ethnic	No	No	Yes	No	No	Yes	No	No	Yes
Pseudo-R^2	0.212	0.520	0.573	0.486	0.599	0.653	0.061	0.142	0.158
Observations	139	117	117	448	336	336	567	437	436

Notes: This Table presents the results of regressions relating the impact of eclipses on the measures of human capital, at the ethnic-group level. Columns (1)–(3) report the findings for the *Writing* variable, Columns (3)–(6) report the results for *Strategy Games* and and (7)–(9) for *Eclipse Explanation*. All regressions follow OLS, except for *Eclipse Explanation* which employs ordered logit. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 14: Marginal effects: Human capital.

Writing		Strategy Games		Eclipse Explanation	
Yes	0.165**	Yes	0.062***	No Explanation	−0.028**
	(0.058)		(0.019)		(0.014)
				Naive	0.015
					(0.010)
				Involve Moon and Sun	0.013**
					(0.005)

Notes: This table presents the marginal effects of the results reported in Table 13 for the three measures of human capital. The full set of controls is considered in the analysis. Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

distinguish them from other equally surprising events. First, they are rare but somewhat regular. Second, setting them aside from volcanic eruptions and earthquakes, solar eclipses are harmless both in terms of human and physical capital. Lastly, total solar eclipses are well distributed across Earth and their effects can be perceived by a large collectivity.

In line with our theory, we find that ethnic groups with higher exposure to solar eclipses score systematically higher in three measures of social complexity: jurisdictional hierarchy, political integration and class stratification. Additionally, we also measure higher levels of technological development and population density. This effect is highly robust even after controlling for a wide range of geographical and ethnic control and is seemingly unaffected by other competing explanations. We rationalise our findings by proposing that solar eclipses —and rare events in general— raise the demand for explanations, therefore exercising thinking. Consequently, we argue that a higher number of solar eclipses would positively affect human capital in its infancy stages. We test this possibility by relating solar eclipses to several variables indicative of deeper thinking and connected to human capital: the development of a written language, the playing of strategy games and the realisation that the Moon intervenes in solar eclipses. In general, this set of additional results lends credence to our hypothesis that ethnic groups more exposed to solar eclipses display higher levels of human capital.

Our research sheds light on the origins of complex societal structures and the emergence of complex thinking, complementing previous findings. We highlight the importance of thinking for development, in line with theories on the importance of human capital, however, we show that curiosity is a prerequisite of knowledge. The data that we have compiled allows us to take a long-term perspective of one —amongst potentially often— trigger of human curiosity.

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A Eclipse prediction in pre-modern times

One possible concern regarding the results is that eclipses were predictable and, hence, that a ruling elite may have used this private knowledge to instil fear and coerce the population. Similarly, it is also possible that ethnic groups particularly afraid or fond of eclipses might have targeted locations with more or less future eclipses as migratory destinations.

This Section addresses these concerns by explaining in detail how pre-modern societies predicted eclipses. It is important to highlight that we deal with two types of predictions: time and location.

The timing of eclipses. All eclipses —solar and lunar— occur when the Sun, Moon and Earth align on the ecliptic plane: the plane on which the Earth orbits the Sun. The Moon's orbit is tilted about 5 degrees with respect to the ecliptic, which implies that two intersection points exist: the nodes.

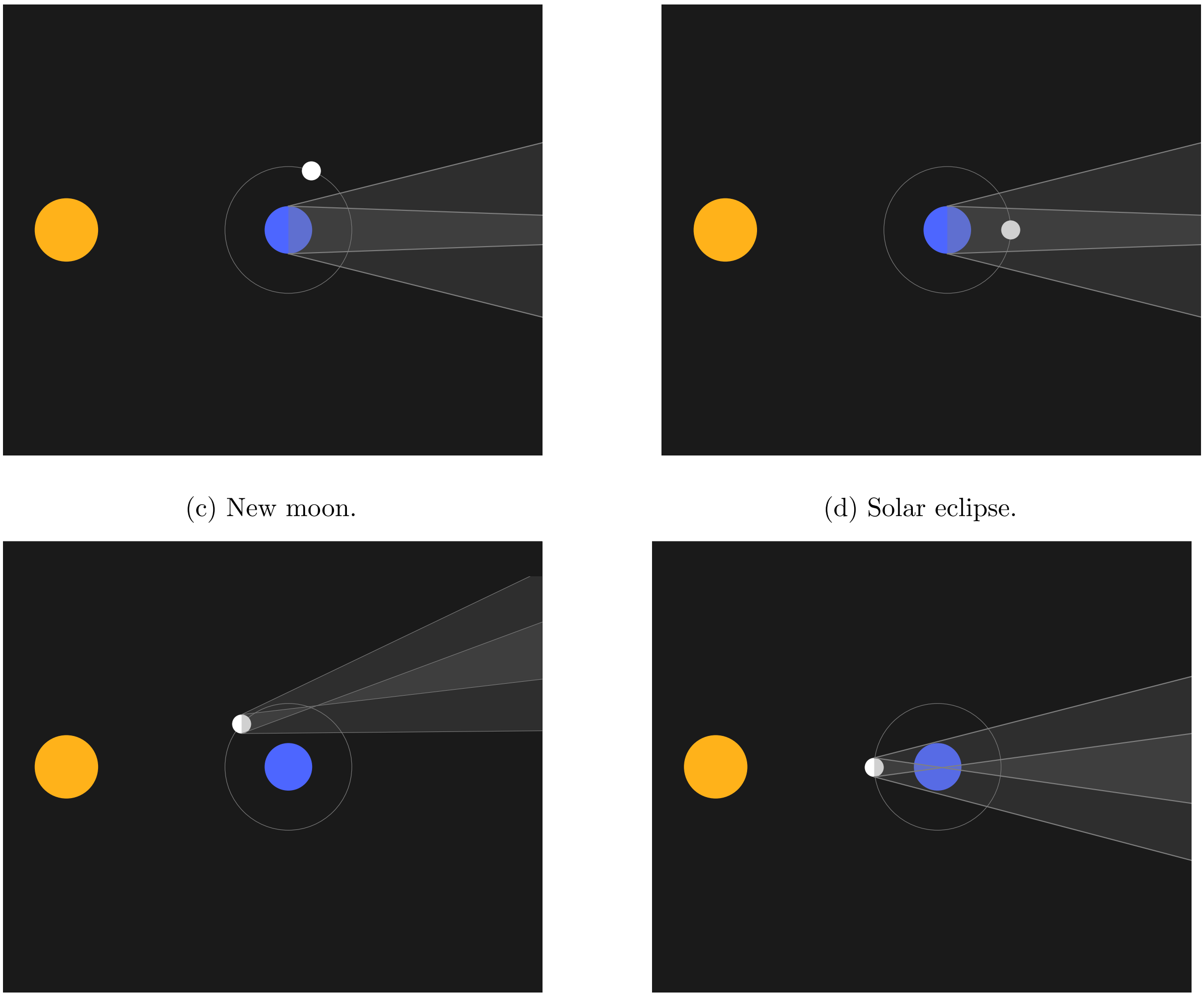
During each new moon, the Moon is situated in the day-time hemisphere. In general, though, it typically passes too high or too low in its orbit to cast any shadow on Earth. However, when the Moon is at one of its nodes during a new moon, it blocks sunlight, casting a shadow on Earth. To an observer on Earth, the Sun slowly enters into the shadowed area, effectively disappearing: a solar eclipse.[38] However, the shadow is too narrow to affect the entire Earth: solar eclipses are very local, roughly spanning 160 km wide.[39] Figure 5 illustrates the special configuration required for eclipses, together with the more common full and new moon situations. Lastly, depending on the distance between the centre of the Moon and the ecliptic, eclipses are partial —the Moon passes too high or too low— or total. The Sun–Moon distance also determines how much of the Sun is covered by the shadow, generating total or annular eclipses.

In summary, solar eclipses require a new moon and the Moon must be sufficiently close to the ecliptic. Pre-modern societies exploited the regularity inherent to these phenomena. The time between two consecutive new moons is called a *synodic month* with a length of 29.53 days. Since the orbital plane of the Moon is tilted about 5 degrees with respect to the ecliptic, eclipses are only possible whenever the Moon crosses the ecliptic. This happens each *draconic month*

[38] Another requirement is for the apparent diameter of the Moon to be roughly similar or larger than that of the Sun. This is, the Moon must appear as large as the Sun, or more, to effectively obscure it. By a fortunate coincidence, the relative distance between the Earth and Sun and the Moon and the Earth coincides with the relative size of the Sun with respect to the Moon when the Moon is closest to the Earth. As the Moon slowly drifts away from Earth, several millennia from now, eclipses will only be annular.

[39] During a regular full moon, the Moon is located opposite the Earth and reflects light from the Sun. However, if it is at its node —or near it—, the Earth blocks sunlight, generating a lunar eclipse. Such phenomena are visible from the entire night hemisphere.

Figure 5: Eclipses, full moon and new moon.



(a) Full moon. (b) Lunar eclipse. (c) New moon. (d) Solar eclipse.

Notes: This figure represents four combinations that produce, respectively, a full moon —5a—, a lunar eclipse —5b—, a new moon —5c— and a solar eclipse —5d. Notice that lunar eclipses are only possible during a full moon and solar eclipses during a new moon. Also, eclipses are only possible near the nodes, this is, when the moon crosses the ecliptic. *Source:* Adapted from Bryant (2011).

with a duration of about 27.2122 days. Combining both, we find that eclipses must be 173.31 days apart: half the beat period between frequencies.[40]

So far, we have been working with only two frequencies: synodic and draconic months. Steele (2000b), Kelley and Milone (2011), Freeth (2014) and others state that another cycle was added to the previous two: the *anomalistic month*. It measures the time it takes for the Moon to have the same apparent size in the sky.[41] When the three cycles coincide, the eclipses are similar: total, partial or annular, and with a similar magnitude. An anomalistic month lasts for 27.554 days, so using the triple-cycle to predict similar eclipses implies that each is separated by 18

[40]The beat period computes the time it takes two different frequencies to come back into synchronisation. For frequencies f_1 and f_2, the beat period equals $\frac{f_1 f_2}{f_1 - f_2}$.

[41]Differences in its apparent diameter are caused by the elliptic orbit it follows around the Earth.

years, 11 days and 8 hours. The triple-cycle is known in the literature as *Saros*, and modern astronomers classify eclipses as belonging to one Saros series.[42] The problem with predicting using the Saros cycles is that two consecutive eclipses do not belong to the same series. However, it is possible to simultaneously follow several Saros cycles.

Others included alternative cycles. For instance, Mesoamericans and Arid America hunter-gatherers counted synodic and sidereal months, see Murray (2014, p. 666).[43] Based on similar principles, the Mayas predicted eight centuries of solar eclipses worldwide (Murray (2014, p. 700)).

Local visibility of eclipses. The system we presented above is most useful at predicting lunar eclipses: these are visible from the entire night hemisphere. It is also capable of accurately predicting solar eclipses, but not local visibility. In fact, solar eclipses present additional challenges. The first one is that the Saros cycle is not an integer number of days. Consider that a total solar eclipse was visible from some location. If the Saros were 18 years and 11 days, the Earth would be in exactly the same position, and the predicted eclipse would be visible from the same location. However, the additional eight hours imply that the Earth has rotated 120 degrees, and the eclipse is visible 120 degrees away from the first one. Taking an even longer cycle of three Saros solves this problem.[44] Nevertheless, there is a second complication for solar eclipses: eclipses from a Saros series present a longitudinal drift. Therefore, even solar eclipses that are three Saros apart are not necessarily visible from the same location. Figure 6 illustrates both the east-west and north-south drifts of the Saros cycles.

The necessary knowledge to derive the timing of eclipses was available to ancient cultures, which were able to predict eclipses.[45] In fact, they were quite apt at it and, by the eighth century BC, Babylonian astronomers published *warning tables* that indicated possible eclipses. However, predicted eclipses were not always visible from Babylonia. As we explained, predicting the local visibility of solar eclipses is far more complex for solar eclipses and requires precise knowledge of the orbits of the Moon and the Earth. Steele (1997) compares solar eclipses predicted by Babylonian astronomers to actual realisations and finds that out of 61 recorded eclipses, only 28

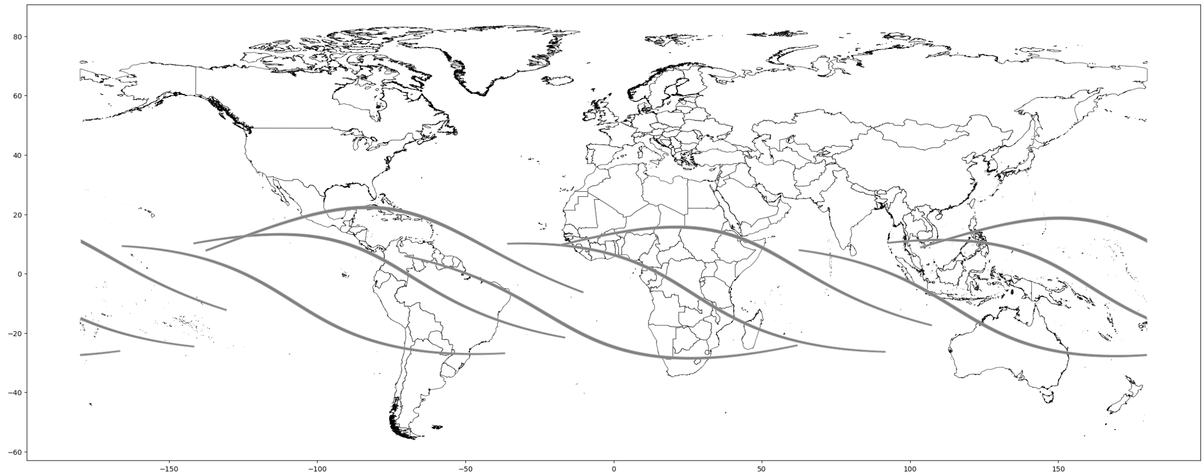
[42]The Saros cycle was already known by Chaldean (neo-Babylonian) astronomers around 600-500BC. Contrary to what it may seem, Saros cycles are finite and preclude long-term predictions. This is so because the numbers discussed before are only approximations, and errors accumulate with time. However, a Saros cycle typically contains 69 to 87 lunar eclipses covering up to 1566 years.

[43]The sidereal month lasts 27.25 days.

[44]Although less acute, the turning of the Earth also affects the local circumstances of lunar eclipses, Steele (2000a, p. 15). Using a triple-Saros cycle completely solves the issue.

[45]Steele (2000b, p. 11) discusses that, since lunar eclipses are visible from the entire night hemisphere, early astronomers based their calculations on them.

Figure 6: Eclipses from Saros 136.



Notes: This Figure represents nine solar eclipses corresponding to the 136 Saros series. Eclipses follow a west and northward shift, preventing local predictions.

were visible from Babylonia. However, all of the 61 solar eclipse predictions correspond to an actual eclipse.

Overall, the complexity associated with accurate predictions of solar eclipses, the irregularity in their location and the limited dissemination of scientific knowledge across societies and across time reinforced the awe associated with solar eclipses versus that caused by other similar phenomena.

B Summary statistics

Table 15 below provides the summary statistics for all the variables we use in our analysis.

Table 15: Summary statistics.

	Mean	*Std.Dev.*	*Min.*	*Max.*
Eclipses				
Number of eclipses	69.117	54.483	13.000	883.000
Avg. time between eclipses(centuries)	0.658	0.300	0.040	2.560
Min. Time between eclipses(centuries)	0.023	0.028	0.000	0.290
Max. Time between eclipses(centuries)	2.857	1.252	0.194	8.575
Number of lunar eclipses(centuries)	1391.167	90.888	1336.000	2443.000
Jurisdictional Hierarchy				
No levels	0.461	0.499	0.000	1.000
One level	0.298	0.458	0.000	1.000
Two levels	0.142	0.349	0.000	1.000
Three levels	0.073	0.260	0.000	1.000
Four levels	0.026	0.159	0.000	1.000

Class Stratification				
Absence among freemen	0.487	0.500	0.000	1.000
Wealth distinctions	0.191	0.393	0.000	1.000
Elite	0.035	0.184	0.000	1.000
Dual	0.213	0.410	0.000	1.000
Complex	0.074	0.262	0.000	1.000
Political Integration				
Absence	0.018	0.132	0.000	1.000
Automous local comm.	0.107	0.309	0.000	1.000
Peace groups	0.007	0.083	0.000	1.000
Minimal states	0.062	0.241	0.000	1.000
Little states	0.023	0.151	0.000	1.000
States	0.034	0.181	0.000	1.000
Technological Level				
Technological Level	9.536	1.492	7.194	13.378
Population Density				
Less than 1 / sq. mile	0.280	0.450	0.000	1.000
1–5 / sq. mile	0.161	0.368	0.000	1.000
5–25 / sq. mile	0.181	0.386	0.000	1.000
25–100 / sq. mile	0.197	0.399	0.000	1.000
100–500 / sq. mile	0.124	0.331	0.000	1.000
500 or more / sq. mile	0.057	0.232	0.000	1.000
Writing				
Writing	0.212	0.410	0.000	1.000
Strategy Games				
Strategy games	0.169	0.375	0.000	1.000
Eclipse Explanation				
No explanation	0.640	0.480	0.000	1.000
Naive	0.258	0.438	0.000	1.000
Involve Moon and Sun	0.102	0.303	0.000	1.000
Annual mean temp.	192.946	89.340	−166522	301.410
Annual precipitation	1327.907	954.285	0.264	6415.639
Ecological diversity	0.420	0.246	0.000	0.839
Dist. coast ()	430.916	412.958	0.054	1648.241
Dist. river ()	248.096	836.981	0.198	8401.051
Dist. Addis Ababa ()	14.675	13.162	0.125	43.844
Ruggedness	86.664	32.505	0.000	199.000
Elevation	162.953	26.374	0.000	210.116
Malaria	0.173	0.206	0.000	0.688
Caloric yield	1170.170	860.545	0.000	4975.770
Abs. latitude	21.443	17.700	0.017	78.070
South (0/1)	0.203	0.403	0.000	1.000
Major Habitat Type				
Boreal forest	0.020	0.140	0.000	1.000
Desert	0.103	0.304	0.000	1.000
Flooded grasslands	0.009	0.096	0.000	1.000
Mangroves	0.012	0.107	0.000	1.000
Mediterranean scrub	0.025	0.155	0.000	1.000
Montane grasslands	0.020	0.140	0.000	1.000
Snow, ice, glaciers,rock	0.003	0.056	0.000	1.000
Tempered broadleaf forests	0.048	0.214	0.000	1.000

Temperate coniferous forests	0.077	0.267	0.000	1.000
Temperate grasslands, savannas	0.039	0.193	0.000	1.000
Tropical coniferous forests	0.016	0.126	0.000	1.000
Tropical dry broadleaf forests	0.044	0.205	0.000	1.000
Tropical grasslands	0.264	0.441	0.000	1.000
Tropical moist broadleaf forests	0.301	0.459	0.000	1.000
Tundra	0.019	0.135	0.000	1.000
Water	0.001	0.028	0.000	1.000
Dependence on gathering (%)	24.149	128.998	2.500	1830.500
Dependence on agriculture (%)	45.249	26.581	2.500	90.500
Intensity of Agriculture				
No agriculture	0.206	0.404	0.000	1.000
Casual agriculture	0.036	0.187	0.000	1.000
Extensive agriculture	0.401	0.490	0.000	1.000
Horticulture	0.083	0.275	0.000	1.000
Intensive agriculture	0.166	0.372	0.000	1.000
Intensive irrigated agriculture	0.109	0.311	0.000	1.000
Major Crop Type				
None	0.213	0.410	0.000	1.000
Non food crop	0.002	0.041	0.000	1.000
Vegetables	0.003	0.050	0.000	1.000
Tree fruits	0.068	0.252	0.000	1.000
Roots or tubers	0.197	0.398	0.000	1.000
Cereal grains	0.517	0.500	0.000	1.000
Subsistence Economy				
Gathering	0.080	0.271	0.000	1.000
Fishing	0.093	0.290	0.000	1.000
Hunting	0.060	0.237	0.000	1.000
Pastoralism	0.061	0.240	0.000	1.000
Extensive agriculture	0.372	0.484	0.000	1.000
Intensive agriculture	0.214	0.410	0.000	1.000
Two or more above	0.051	0.220	0.000	1.000
Agriculture, unknown type	0.070	0.255	0.000	1.000

C Additional Tables

In Table 16, Panels A to H report the results of the benchmark specification for all five measures of complexity when using alternative periods to compute the total number of eclipses. Since the correlation between the number of total solar eclipses in different periods of time is quite large, we expect results not to differ between them either with respect to the baseline specification.

Figure 7: Geographical distribution of outcomes.

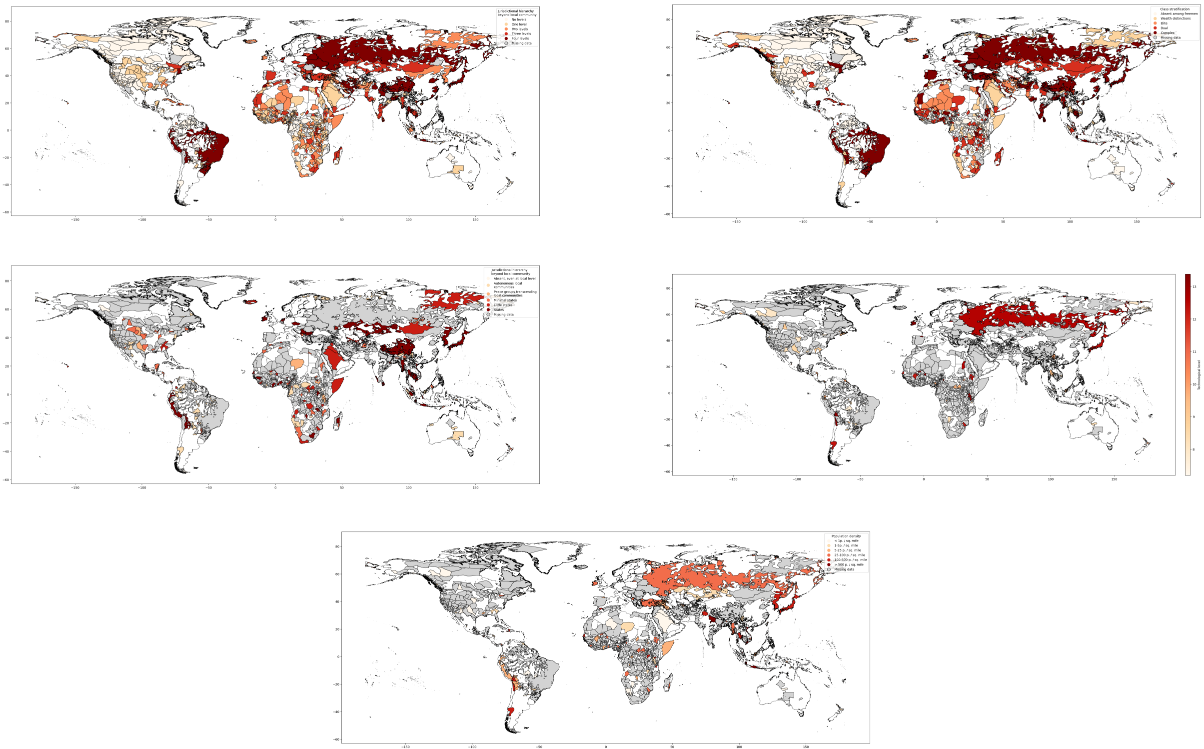


Table 16: Robustness: Alternative time frames.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
	Panel A: 2000BC - 1500BC				
Eclipses	0.054***	0.072***	0.049**	0.033**	0.119***
2000BC - 1500BC	(0.013)	(0.021)	(0.020)	(0.015)	(0.035)
R^2 Pseudo-R^2	0.262	0.261	0.179	0.706	0.459
Observations	911	255	825	108	139
	Panel B: 1500BC - 1000BC				
Eclipses	0.052***	0.035	0.033**	0.027*	0.123***
1500BC - 1000BC	(0.016)	(0.030)	(0.014)	(0.014)	(0.044)
R^2 Pseudo-R^2	0.262	0.253	0.175	0.703	0.459
Observations	911	255	825	108	139
	Panel C: 1000BC - 500BC				
Eclipses	0.037**	0.034	0.041***	0.024**	0.085**
1000BC - 500BC	(0.015)	(0.025)	(0.011)	(0.010)	(0.037)
R^2 Pseudo-R^2	0.259	0.254	0.177	0.705	0.448
Observations	911	255	825	108	139
	Panel D: 500BC - 0				

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Table 16 – *Continued from previous page*

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
Eclipses 500BC - 0	0.035*	0.068*	0.031**	0.030*	0.108***
	(0.020)	(0.037)	(0.016)	(0.015)	(0.036)
R^2 Pseudo-R^2	0.258	0.257	0.175	0.704	0.450
Observations	911	255	825	108	139
	Panel E: 0 - 500				
Eclipses 0 - 500	0.053***	0.074***	0.062***	0.027**	0.103**
	(0.014)	(0.027)	(0.022)	(0.010)	(0.040)
R^2 Pseudo-R^2	0.262	0.261	0.181	0.703	0.451
Observations	911	255	825	108	139
	Panel F: 500 - 1000				
Eclipses 500 - 1000	0.046***	0.052**	0.057**	0.038***	0.085***
	(0.015)	(0.024)	(0.024)	(0.012)	(0.032)
R^2 Pseudo-R^2	0.261	0.257	0.181	0.720	0.448
Observations	911	255	825	108	139
	Panel G: 1000 - 1500				
Eclipses 1000 - 1500	0.054***	0.066***	0.040***	0.015*	0.087***
	(0.019)	(0.021)	(0.015)	(0.008)	(0.033)
R^2 Pseudo-R^2	0.262	0.260	0.176	0.695	0.447
Observations	911	255	825	108	139
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: This table reports the results of the benchmark specification for all six measures of economic development, when using each of the alternative eight measures of eclipses. These correspond to the number of total eclipses for the following periods: 2000BCE-1500BCE, 1500BCE-1000BCE, 1000BCE-500BCE, 500BCE-0CE, 0CE-500CE, 500CE-1000CE, 1000CE-1500CE, 1500CE-2000CE. The full set of controls is considered in the robustness analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.$^{*}\,p < 0.1$, $^{**}\,p < 0.05$, $^{***}\,p < 0.01$.

As anticipated, our results in Table 16 suggest that the effect is present no matter which measure we use. Moreover, the magnitude is also quite similar with no systematic differences across periods or measures.

Table 17 presents the results when we control for additional ethnic-group characteristics in the regressions. Panels (A) and (B) include dependence on gathering and agriculture, respectively while Panel (C) introduces agricultural intensity levels. Panel (D) includes fixed effects for the subsistence mode of production.

Table 17: Robustness: Additional ethnic controls.

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
			Panel A: Gathering		
Total number	0.007***	0.008**	0.007***	0.004**	0.013*
of eclipses	(0.002)	(0.004)	(0.003)	(0.002)	(0.007)
Dependence on	−0.311***	−0.432***	−0.346***	−0.420**	−1.173***
gathering	(0.077)	(0.080)	(0.074)	(0.190)	(0.431)
R^2 Pseudo-R^2	0.267	0.271	0.187	0.759	0.483
Observations	911	255	825	108	139
			Panel B: Agriculture		
Total number	0.008***	0.011***	0.008***	0.005*	0.014**
of eclipses	(0.002)	(0.004)	(0.003)	(0.002)	(0.006)
Dependence on	0.065	0.114	0.190***	−0.111	0.752***
agriculture	(0.063)	(0.075)	(0.066)	(0.157)	(0.209)
R^2 Pseudo-R^2	0.262	0.260	0.183	0.710	0.482
Observations	911	255	825	108	139
			Panel C: Major Crop Type		
Total number	0.008***	0.008	0.008***	0.004**	0.015**
of eclipses	(0.002)	(0.005)	(0.003)	(0.002)	(0.006)
Crop type					
No agric.	Ref.	Ref.	Ref.		
Non food crops.	0.911	−2.013	1.556		
	(1.340)	(2.526)	(3.840)		
Vegetables	−0.176	−4.930***	−0.713		
	(1.347)	(1.627)	(0.905)		
Tree fruits	−0.095	−2.463*	−0.702	1.064*	−12.801***
	(1.287)	(1.381)	(1.431)	(0.592)	(2.569)
Roots	−0.082	−2.946**	−0.696	0.912	−15.282***
	(0.982)	(1.153)	(1.255)	(0.538)	(2.384)
Cereals	−0.150	−2.658**	−1.012	0.902	−13.306***
	(0.890)	(1.096)	(1.213)	(0.552)	(2.047)
R^2 Pseudo-R^2	0.262	0.263	0.181	0.706	0.477
Observations	911	255	825	108	139
			Panel D: Subsistence economoy		
Total number	0.008***	0.011**	0.007***	0.004*	0.017***
of eclipses	(0.002)	(0.004)	(0.002)	(0.002)	(0.006)
Subsistence					
Gathering	Ref.	Ref.	Ref.	Ref.	Ref.

Continued on next page

Table 17 – *Continued from previous page*

	Jurisdict. Hierarchy	Pol. Int.	Class Strat.	Tech. Level	Pop. Den.
	(1)	(2)	(3)	(4)	(5)
Fishing	0.428	-0.778^{*}	0.986^{**}	0.970	2.449
	(0.448)	(0.467)	(0.397)	(0.667)	(4.996)
Hunting	0.346	0.635^{**}	-0.607	0.738	-13.763^{***}
	(0.472)	(0.311)	(0.541)	(0.561)	(2.707)
Pastoralism	0.954^{**}	0.933	0.291	1.947	3.904
	(0.483)	(0.576)	(0.521)	(1.553)	(5.604)
Int. agric.	0.426	-0.247	0.702	1.257^{**}	3.426^{*}
	(0.438)	(0.517)	(0.635)	(0.523)	(1.866)
Two or more	1.026^{*}	1.276^{*}	1.255^{**}	3.906^{***}	7.919
	(0.538)	(0.688)	(0.611)	(1.307)	(5.608)
Agric.	0.309	-0.280	0.405	2.758^{***}	5.304
	(0.472)	(0.642)	(0.623)	(0.889)	(4.575)
R^2 Pseudo-R^2	0.264	0.268	0.187	0.769	0.490
Observations	911	255	825	108	139
Controls (common to all regressions)					
Fixed effects	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	Yes	Yes	Yes
Ethnic	Yes	Yes	Yes	Yes	Yes

Notes: This table reports the results when we add controls for a wide range of ethnic and geographical controls as well as various fixed effects. Panels (A) and (B) include dependence on gathering and agriculture. Panel (C) introduces agricultural intensity levels. Panel (D) includes fixed effects for the subsistence mode of production. The full set of controls is considered in the robustness analysis. Continent fixed effects: indicators for Asia, Europe, Africa, North America, South America and Oceania.Geographic controls: average temperature and precipitation, distance to the coast, to the closest river and terrestrial distance to Addis Ababa, terrain ruggedness, elevation, malaria prevalence, soil potential caloric yield, absolute latitude, south indicator and major habitat type indicator.Ethnic controls: major crop type indicator.Robust standard errors in parentheses clustered at the regional level.* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

In general, the results indicate that agriculturalists exhibit more complex social structures. This is in line with comparative development theories, namely, the impact of the Neolithic revolution (Diamond (2017)). According to Litina and Bertinelli (2014), similar findings arise for irrigation and intensive agriculture. However, the introduction of such variables does not alter our main result.