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CHARACTERIZING THE PHOTOMETRIC VARIABILITY AND ACCRETION DISK OF V346 NORMAE

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ABSTRACT

FU Orionis (FUor) stars are pre-main-sequence stars that have exhibited a sharp increase in brightness (6 magnitudes) over at most multiple decades, as a result of an enhanced rate of accretion of mass from the inner region of the circumstellar disk onto the star. One such star, V346 Normae, erupted around 1980. From 2008 to 2010, its brightness decreased dramatically. After reaching a minimum in 2010, it has erupted again, and continues to increase in brightness towards its original maximum. The mechanism of this dramatic decrease and immediate subsequent increase in brightness is unknown. By analyzing its small-scale variability in an accreting star's brightness, it is possible to infer the physical properties of its accretion disk. We propose a continuous analysis of V346 Normae's small-scale variability, so that its accretion disk's physical properties can be monitored, and its changes tracked through time. Equipped with new information about its accretion disk's changes, it will be possible to constrain the possible mechanisms for its dimming and current eruption.

Keywords: FU Orionis, accretion disk, V346 Normae, pre-main-sequence stars

1. RECENT PROGRESS

FU Orionis (FUor) stars are those that have exhibited a dramatic outburst, increasing in brightness by up to six magnitudes over periods of hundreds of days to multiple decades. After reaching maximum brightness, they maintain that brightness, or decline slightly (by one or two magnitudes) over 10^2 to 10^3 years (Hartmann & Kenyon 1996). This outburst is attributed to an increased rate of mass accretion onto a star, initiated by an instability in the inner regions of its circumstellar accretion disk (Turner et al. 1997). The outburst of FUor stars an important event in the early evolution of certain stars, possibly including the Sun (Herbig 1977), and may provide insights into the formation of planetary systems (Turner et al. 1997).

Recently, advancements have been made in the characterizing the accretion disk of FUor stars by analyzing their photometric variability. Kenyon et al. (2000) noted that while accretion disks very commonly exhibit flickering (random brightness fluctuations, with an amplitude of 0.01 to 1.0 magnitudes, and on dynamical timescales), such that flickering is their "signature", flickering behaviour had never been observed in FUor stars. They analyzed the short-term variability of eponymous star FU Orionis's light curve, looking for flickering, and in doing so they gained some hints about the properties of the accretion disk. They found variability, with no sign of periodicity, on the time scale of ≤ 1 day, accompanied by correlated variations in the star's colour indices. The variations in the colour indices had the optical colours of a G0 supergiant, with a temperature of approximately 6000K. From this piece of information, some interesting properties of the accretion disk were inferred. Kenyon et al. determined that using a simple, steady disk model, the observed colour variation can only be produced when specific annuli in the accretion disk, corresponding to the colours of F9 to G1 supergiants, are allowed to vary. However, in simply steady disk models, these annuli occur at a radius of about $R = 2.5R_*$, with a maximum temperature annulus at $R = 1.36R_*$. However, there are hotter annuli, at temperatures of 6500-7000K, at smaller radii. These hotter annuli at smaller radii ought to exhibit larger variation than cooler annuli at larger radii, if the simple steady disk model is accurate. Since the flickering is not exhibited at these temperatures, the simple steady disk model is unable to predict the observed flickering behaviour.

Instead, the flickering behaviour is explainable by models that assume an optically thicker disk. These models predict peak temperatures of approximately 7000K at radii of $R = 1.1 - 1.2R_*$. Importantly, they also predict disk temperatures of approximately 5000-6000K immediately outside the star's photosphere, at radii smaller than that of the peak temperature. With temperatures comparable to the flickering source occurring immediately outside the photosphere, it is permissible for variation to occur specifically in the observed colours. Thus, the observation of a 6000K flickering source characterizes the accretion disk in two ways: first, it serves as evidence in favour of models with optically thick accretion disks around FUor stars, and second, it indicates that the flickering source is the inner edge of the accretion disk, very near to the star, between the star's photosphere and the maximum temperature annulus. In order to produce the observed fickering, it is this inner edge of the accretion disk that must have exhibit rapid, large-scale changes in physical structure. The authors conclude the paper by stating that with higher-precision photometry investigating this flickering, it will be possible to probe in greater detail the conditions of the accretion disk.

The question of small-scale photometric variability in FU Orionis was investigated again by Siwak et al. (2013). They characterized its variability by conducting wavelet analysis on photometric observations by the MOST satellite. They confirmed the result of Kenyon et al. (2000), concerning the temperature of the source of small-scale variability (i.e. flickering), while also finding several different quasi-periodic features with periods of two to nine days. Over the course of the 28 days during which the observations took place, their periods shorten slightly, with 9-day features shortening to 8 days, and 2.4-day features shortening to 2.2 days. These features are similar to those seen in the T Tauri star TW Hydrae by Rucinski et al. (2008) and Siwak et al. (2011); they are intepreted to be inhomogeneities in the accretion disk, such as plasma concentrations, produced by interactions between the star's magnetic field and the plasma of the inner edge of the accretion disk. The gradual decrease in period occurs as these plasma concentrations spiral towards the centre of the accretion disk.

Both Kenyon et al. (2000) and Siwak et al. (2013) have been characterizing the accretion disk around FU Orionis by analyzing its small-scale photometric variability. These methods have great potential for use in characterizing another star of the FUor type: V346 Normae. V346 Normae exhibited a strong outburst, like other members of the FUor type, around 1980. Kraus et al. (2016) reported that between the 1990s and 2010, its visual/near-infrared brightness decreased dramatically, indicating a drop of several orders of magnitude in accretion rate. Kóspál et al. (2017) found that this decrease was very short and sudden, occurring entirely in the late 2000s. V346 Normae's brightness reached a minimum in 2010 (Kóspál et al. 2017), and since 2011, it has been growing brighter once again, entering a second outburst (Kraus et al. 2016). It has not yet reached its maximum brightness from before the dimming event.

Kóspál et al. (2017) also note that observations of V346 Normae have fallen on a mostly straight line on an HR diagram, up until 2008, when the dimming event starts. In 2008, the slope of the line traced by its observations became more negative, deviating from the linear trend of previous observations. That is, its decrease in brightness (and increase in mangnitude) from 2008 to the minimum 2010 was accompanied by a smaller reddening than would be expected from its previous observations. As it enters its second outburst, from 2010 to present, it retraces the curve of its decrease. The deviation of recent observations from its previous trends suggests that the dimming and present intensifying event are results of a different mechanism than the one responsible for the original, typical FUor outburst. While the initial outburst was produced by simultaneous increases in accretion rate and in extinction, the dimming event was produced by a dramatically decreasing accretion rate alone. Since V346 Normae is returning to its 2008 position on the HR diagram, its current increasing event is likely the reverse process, with accretion dramatically increasing as extinction maintains a constant rate. Indeed, Kóspál et al. (2017) found that they could reproduce V346 Normae's spectral energy distribution (SED) through its original outburst, until 2008, by varying its accretion and extinction rates in tandem, and from 2008, through its dimming and intensifying, by varying accretion rate alone, while holding extinction at its constant, high rate.

A similar pattern of rapid dimming and re-intensifying, resulting from a varying accretion rate, has been observed in other stars, including the outbursting protostar V899 Mon, a new member of the FUor/EXor family. Ninan et al. (2015) put forth several possible explanations for V899 Mon's sharp dimming and intensifying. One possible mechanism is instability in the star's magnetic accretion funnels. Differential rotation between the star and its inner accretion disk cause its magnetic field lines to open and reconnect; this can greatly reduce accretion, while increasing outflow/jets from the star, as observed in V899 Mon. Soon afterwards, the magnetic field lines are restored to their original state, and so the accretion and outflows return to normal (Bouvier et al. 2003), corresponding to V899 Mon's intensifying. Another possible mechanism is that as mass accretes onto the star, the inner edge of the accretion disk moves outwards, away from the star. When it becomes larger the corotation radius, accretion stops, and the disk's mass piles up near the inner edge. As a result, the inner radius contracts again, and when it crosses the corotation radius, accretion resumes. This process repeats, and the accretion rate oscillates (D'Angelo & Spruit 2010). In this case, V899 Mon and V346 Normae may have been observed in the first of many such periods.

While these mechanisms are all plausible explanations for V899 Mon's observed behaviour, and perhaps V346 Normae's similar variations in brightness, they have never been explicitly demonstrated. Not enough is presently known about the accretion disk of either star to definitively decide on any mechanism. Using the methods of Kenyon et al. (2000) and Siwak et al. (2013), it would be possible to learn more about the physical properties of V346 Normae's accretion disk by analyzing its small-scale variability, and take substantial steps towards determining the mechanism of its recent brightness fluctuation. This understanding would advance the understanding of similar stars like V899 Mon, and of FUors in general.

2. OBJECTIVES

It would be very informative to know what the accretion disk around V346 Normae is like as it enters its second outburst, since, after all, the outbursts are a results of increased accretion. The objective of this project is to continuously analyze the small-scale photometric variability of V346 Normae as it is entering its second observed outburst, in order to infer the properties of the accretion disk, and how they change, over the course of the outburst's initiation. Ultimately, in characterizing the accretion disk, and its changes over time as the outburst begins, we will gain a better understanding of the processes that underlie the outbursts of FUor stars.

3. LITERATURE REVIEW

The FUor class is named after FU Orionis, a star in the constellation Orion, which increased in brightness by 6 magnitudes within a year, in 1937. Since then, more than two dozen FUors and FUor candidates have been found, including of course the star of interest, V346 Normae, all of which exhibit similar increases in brightness (Audard et al. 2014). FUors are pre-main-sequence stars, found in active star-forming regions of the Milky Way (Herbig 1966, 1977; Hartmann & Kenyon 1996; Kenyon 1999). Other pre-main-sequence stars, including T Tauri stars, Herbig Ae/Be stars, and EXors, also exhibit brightness variations at irregular intervals, but the amplitude of their variation is smaller (Appenzeller & Mundt 1989; Herbig 2008; Hillenbrand et al. 1992).

The increase in brightness of these FUor stars is a result of an increased accretion rate onto the star, from the inner region of a circumstellar accretion disk (Turner et al. 1997). FUor outburst models predict a periodicity in their eruptions. The inner region of a FUor star's accretion disk depletes as it accretes rapidly onto the star, and the eruption ends when it depletes entirely. With halted accretion, mass can gradually accumulate again at the inner region of the disk. Once the inner disk reaches a sufficient mass to trigger another instability, like that responsible for the original eruption, another eruption occurs. The replenishing of the inner disk takes several thousands, or tens of thousands, of years (Bell & Lin 1993).

Recently, FUor stars, including V346 Normae and V899 Mon, have been observed decreasing dramatically in brightness, signifying an underlying decrease in accretion rate Kraus et al. (2016); Ninan et al. (2015). However, they have not remained in their dimmer, quiescent state for long. V346 Normae started decreasig in brightness from 2008 until a minimum in 2010, and is already increasing again towards its maximum brightness (Kóspál et al. 2017). V899 Mon similarly paused its outburst for less than a year, immediately returning to its outburst state (Ninan et al. 2015). These quiescent states are far too short to be explained by a depleted inner accretion disk, so other mechanisms, as discussed in Section 1, have been put forth by Ninan et al. (2015). While the speculated mechanisms fit with observed properties of FUors, not enough is presently known about FUors' accretion disks to accept any of the proposed possibilities.

4. METHODOLOGY

The analysis of the small-scale photometric variations of V346 Normae will require its monitoring from multiple sources, preferably for as long as its brightness continues to increase.

First, it will be necessary to model the large-scale increase in brightness (i.e. the outburst itself), so that the small-scale variations can be subtracted from it. This is because the small-scale variations are individual measurements' residuals from the large-scale increase. Since the large-scale increase in brightness spans several years, the observations used to model it need not be frequent, on the order of individual days. Following the example of Kenyon et al. (2000), visual observation by members of the American Association of Variable Star Observers (AAVSO) is sufficient to establish a long-term light curve to model the outburst on a large scale. A request for observations will be made to the AAVSO, and observers worldwide (strictly speaking, observers at latitudes between +30 and -90 degrees) will help construct a long-term light curve for the construction of this model.

At the same time, a request will be sent for the Mount John University Observatory 61cm telescope (OC61), one of the AAVSOnet network of robotically controlled telescopes, to, for one week each month, observe V346 Normae once each night with Johnson-Cousins B and V filters. These observations are those that will pick up on the small-scale photometric variations to be analyzed. It is necessary to take frequent (i.e. each night) observations, since the small-scale variations occur on that scale. However, requests for observations should be kept somewhat modest. Thus, nightly observations for one week each month (preferably for as long as V346 Normae continues to increase in brightness) allow for continuous monitoring, at the required frequency, sampling evenly through time. The purpose of the previously discussed visual observations by AAVSO members is to fill the gaps between these periods with lower-frequency and perhaps less precise measurements, that are nonetheless sufficient to model the long-term increase in brightness.

Like Kenyon et al. (2000) and Siwak et al. (2013), the small-scale fluctuations (i.e. the residuals from the long-term fluctuation, modelled by visual AAVSO data) will be analyzed to produce information about the physical properties of V346 Normae's accretion disk. However, they analyzed FU Orionis's small-scale fluctuations while it was mid-outburst (as it still is today), with a brightness that only slightly decreased over the course of their observation. This project, on the other hand, will observe and analyze V346 Normae's small-scale fluctuations while it is still erupting, with its brightness increasing at a much faster rate as it approaches its original maximum. During this time, as its accretion rate increases, the properties of the accretion disk are changing significantly. Multiple analyses of its fluctuation must therefore be performed, at different points in time throughout this increase. At each point in time, the analysis of the star's fluctuation will reveal its accretion disk's physical properties. By seeing how these properties change in subsequent analyses, as time goes on, this analysis will reveal how the disk changes physically over the course of the eruption.

5. IMPACT

The physical mechanism of V346 Normae's temporary stop and subsequent increase in accretion rate is still unknown (Kóspál et al. 2017). Ninan et al. (2015) put forth several possibilities, as discussed in Section 1, but too little is known about FUors' accretion disks to confirm any of them.

This research on the small-scale brightness variations of V346 Normae would add to the body of knowledge about its accretion disk. Upon this information, models and physical mechanisms for the short-term halt in accretion seen in it, and in other similar stars, can be built. The mechanisms speculated by Ninan et al. (2015) could be tested against the information about V346 Normae's accretion disk, gained from this analysis of its small-scale variability. Perhaps one of them can be confirmed, or perhaps both will be refuted and a novel mechanism will be speculated, on the basis of a more complete knowledge of accretion disks.

In the future, other FUors can be monitored for sudden, short-term quiescent periods like those seen in V346 Normae and V899 Mon. If any FUors do have similar, brief quiescent periods, their small-scale fluctuations can be analyzed in the same way, and compared with those of V346 Normae. If several stars exhibit similar small-scale fluctuations, they will constitute more robust evidence for any proposed mechanism. If they exhibit different small-scale fluctuations, perhaps there are multiple different mechanisms at work, for different individual stars!

It would also be useful to analyze, in the same way, the small-scale fluctuations of FUors during their original eruptions, as their brightness is increasing for the first time. The fluctuations could then be compared with those of starrs like V346 Normae. In this way, the properties of the accretion disk, and how it changes over time, can be more directly compared between the first and second eruptions of FUor stars.

Since FUors are pre-main-sequence stars, a better understanding of them, and of their circumstellar disks, is a better understanding of the early life of very many stars in the Milky Way, likely including the Sun (Herbig 1977). It may even contribute to models of planet formation! The instabilities that trigger FUor eruptions may be caused by massive planets in the circumstellar disk, migrating inwards (Lodato & Clarke 2004). It may be, then, that young giant planets tend to be tidally destroyed by their young host stars (Nayakshin & Lodato 2012). These possibilities highlight the relationship between young stars' eruption events and the planetary systems that can form around them.

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