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Are superflares on solar analogues caused by extra-solar planets?

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ABSTRACT

Stellar flares with $10^2 - 10^7$ times more energy than the largest solar flare have been detected from 9 normal F and G main sequence stars (Schaefer, King & Deliyannis 1999). These superflares have durations of hours to days and are visible from at least x-ray to optical frequencies. The absence of world-spanning aurorae in historical records and of anomalous extinctions in the geological record indicate that our Sun likely does not suffer superflares. In seeking to explain this new phenomenon, we are struck by its similarity to large stellar flares on RS Canum Venaticorum binary systems, which are caused by magnetic reconnection events associated with the tangling of magnetic fields between the two stars. The superflare stars are certainly not of this class, although we propose a similar flare mechanism. That is, superflares are caused by magnetic reconnection between fields of the primary star and a close-in Jovian planet. Thus, by only invoking known planetary properties and reconnection scenarios, we can explain the energies, durations, and spectra of superflares, as well as explain why our Sun does not have such events.

Subject headings: extra-solar planets — magnetic fields — stars: flare — stars: individual (κ Ceti, π^1 UMa) — stars: late-type — stars: magnetic fields

1. Introduction

The discovery (Schaefer, King & Deliyannis 1999) that some solar analogues have large stellar flares is intriguing. The consequences of our Sun experiencing such a "superflare" (SF) would be catastrophic for life on Earth, so it is a relief that the Sun apparently has not had any superflares. Still, we are strongly motivated to determine the cause of

these outbursts. We also want to understand if the Sun could conceivably experience such a superflare, whether potentially life-bearing stellar systems might be affected by these outbursts, and how to predict which systems might be subjected to these outbursts.

The SFs occur on main sequence stars in spectral class F8 to G8 with no unusual properties (specifically rapid rotation, high chromospheric activity, close binary companions, or very young age). The observed SF energy ranges from 10^{33} to 10^{38} erg, although the bolometric correction will in all cases substantially increase the required total energy. The typical SF duration is about one hour, although the range is from a fraction of an hour up to days. SFs emit radiation at least from the x-rays to the optical, with indicated temperatures (Schaefer, King & Deliyannis 1999) from > 15000 K (from the HeI emission line) to ~ 10 keV (from x-ray continuum fits). Our Sun has definitely not had any SFs in the last five centuries (due to the lack of global aurorae) or SFs with $> 10^{36}$ erg in the last billion years or so (due to the lack of appropriate extinctions in the geologic record). Any SF model must satisfy four constraints: the energy budget, the outburst duration, the broad range of emitted light frequencies, and the lack of SFs on our Sun.

2. Model by analogy

As guidance for our model, we note that there exists a well-known class of F and G main sequence stars with large ($\sim 10^{33}$ to 10^{38} erg) flares that last from hours to days visible from x-ray to optical frequencies (Mathioudakis et al. 1992). This group is named after the prototype star RS Canum Venaticorum, or RS CVn. These RS CVn systems are defined as binary stars that have an orbital period between 1 and 14 days in which the hotter component is an F or G type main sequence star and Ca II H&K emission is strong at all orbital phases (Hall 1976, 1989). The close binary companion tidally spins up the F or G main sequence star, which is revealed by high rotational velocity ($\gtrsim 15$ km s^{-1},

Hall 1989), high chromospheric activity (Hall 1976) (typically S> 0.5 Duncan et al. 1991)), high x-ray luminosity (Strassmeier et al. 1993) ($\gtrsim 3x10^{29}$ erg s^{-1}), and detectable orbital radial velocity variations (Simon, Linsky & Schiffer 1980). RS CVn flares are thought to be caused by magnetic reconnections mediated by the close companion star (Simon, Linsky & Schiffer 1980 and Gunn et al., 1997).

The properties of SFs and RS CVn flares are sufficiently close that a similarity of mechanism is suggested. Nevertheless, the nine SF stars reported by Schaefer, King, and Deliyannis are definitely not RS CVn binaries. This is known because the SF stars have low measured rotational velocities (< 9.7 km/s), low Ca II H&K emission (S< 0.367), low x-ray luminosities ($\lesssim 3x10^{29}$ erg s$^-1$), and no detectable radial velocity variations (Schaefer, King & Deliyannis, 1999). It appears as if the SF stars are like RS CVn stars except that the close companion has not tidally spun-up the F or G main sequence star.

What type of close binary companion could mediate a magnetic reconnection (MR) event yet not spin-up the primary star? The answer to this question could come from the recent discovery that many F and G main sequence stars have close planetary companions comparable or larger in mass than Jupiter (Marcy & Butler 1998, Butler et al. 1998). Such Jovian planets would not spin-up their primary star, and hence there will be no abnormal rotation velocity, chromospheric activity, or x-ray luminosity. The expected radial velocity variations of the primary star will be small and unobservable without extremely careful study. Presumably, the Jovian planet will have a dynamo-enhanced magnetic dipole moment comparable to or larger than that of Jupiter which can tangle up the field of the primary star.

So we propose that the SFs occur on otherwise normal F and G main sequence stars with a close Jovian companion, with the superflare itself caused by magnetic reconnection in the field of the primary star mediated by the planet. Our proposed mechanism has

the advantage that it is known to work in a similar physical setting. This hypothesis also has the advantage that no exotic or rare ingredients are required. Indeed, the common occurrence of close Jovian planets creating settings similar to that of RS CVn systems may perhaps produce superflares on many normal solar-type stars.

Our proposed model for superflares on normal stars is similar to the model proposed for large stellar flares on RS CVn binaries. The magnetic fields of the primary star and the planet will interact in two ways. First, the field lines connecting the pair will be wrapped by orbital motion increasing the stress tensor which will manifest as increasing magnetic field strength (Katz 1999). Second, the interaction of specific field loops with the passing planet will initiate a reconnection event similar to that proposed by Simon, Linsky & Schiffer (1980) and Gunn et al. (1997) for large RS CVn flares. Presumably, the planetary motion increases the primary's magnetic field, the interaction of magnetic loops then leads to magnetic reconnection in the space between the star and planet, Alfven waves are generated which propagate toward the star, and the magnetic energy in the Alfven waves accelerates particles near the stellar surface to emit x-rays and optical light (see Haisch, Strong & Rodono 1991 for a review of the related physics of solar flares). Alternatively, the reconnection might occur near the surface of the star where the higher particle density leads to a lower Alfven velocity (Lazarian 1999).

Indeed, this latter case is likely what happened for the κ Ceti superflare. Robinson & Bopp's (1987) observation of the $5876\mathring{A}$ He D_3 line in emission (the transition between $1s2p^3P$ and $1s3d^3D$ states) indicates an outburst at or close to the stellar photosphere. This line is observed in emission from significant solar flares (type 2 or greater) when the plasma density is $n_{e^-} > 10^{14} cm^{-3}$ (Feldman, Liggett & Zirin 1983). Solar models (Allen 1973) indicate that this is the electron density essentially at the photosphere.

Unfortunately, it is difficult to be specific with regards to the physical mechanism of

the explosion since we still do not have a detailed understanding of MR energy release mechanisms despite active research into magnetic reconnection events in laboratory plasmas (Ji et al. 1998, Wesson et al. 1997, Yamada et al. 1997, Ono et al. 1996) and terrestial/planetary magnetospheres (Russell et al. 1998, Russell et al. 1997). The physics of the magnetic reconnection in well-observed solar flares (Antiochos, Devore & Klimchuk 1999, Somov & Kosugi 1997, Haisch, Strong & Rodono 1991) and RS CVn systems (Ferreira 1998) are also only crudely known. There are still significant differences between competing theoretical models of how MR unfolds (Lazarian & Vishniac 1999, Hanato et al. 1998, Biskamp 1997, Pellat, Hurricane & Luciani 1996, Biskamp, Schwarz & Drake 1995). So any SF MR model cannot provide a unique physical explanation of the magnetic reconnection mechanism.

Despite the uncertainties in the detailed physics, we do know that magnetic reconnection occurs in physical settings similar to those of a G-star with a magnetized companion. Fortunately, even without knowledge of the detailed physics, we can still make estimates of the energy budget, the burst duration, and the flare spectrum.

The total magnetic energy outside the star will be equal to $B^2/8\pi$ times the volume of the star for a dipole field, with B equal to the field strength at the surface of the star. For total annihilation of the field outside a solar-size star, the required B varies from 6 to 1200 Gauss for the observed range of SF energy (from $2x10^{33}$ to $9x10^{37}$ erg). However, the energy in a dipole configuration will not reconnect to provide available energy. In general, only some fraction, f, of the magnetic field will be in higher order moments susceptible to reconnection. With this fraction, the available energy for the flare then becomes $E = (B^2/8\pi)(4\pi R^3/3)f$. If f is large, say 0.1, as possible for significant flux caused by the winding of the primary's field, then the associated field strength for a SF would range from roughly 10 to 3000 Gauss. If f is relatively small, say 0.001, as appropriate for a large spot,

then the surface field strength will depend on the exact structure of the field, although the above formula would suggest a field strength of order 100 to 30000 Gauss. With individual spots on our Sun having characteristic fields of up to 3000 Gauss, these required magnetic field energies do not seem unreasonable for SF stars. The observed magnetic energy on our Sun would be sufficient to power a SF, if only a mechanism (such as interactions with a nearby planetary dipole) would allow for reconnection. For the most energetic superflares or to allow for inefficiencies in the conversion of magnetic to radiative energy, we expect that the surface magnetic fields on SF stars might be larger than the values quoted above.

So we are predicting that SF stars likely have magnetic fields substantially higher than on our own Sun. The measure of magnetic field strength on solar-type stars is not easy and is best performed only on bright stars. To date, only two of the nine known SF stars have measured magnetic field strengths. κ Ceti has a magnetic field strength of 1500 Gauss over about 35% of its surface (Montesinos & Jordan 1993). π^1 UMa has an average surface field of 1900 Gauss (Gray 1984). These fields imply total magnetic energies of $\approx 2x10^{37}$ and $2x10^{38}$ ergs respectively. With observed SF energies of $2x10^{34}$ and $2x10^{33}$ ergs, the two SFs used only 10^{-3} and 10^{-5} of the magnetic energy available on the stars respectively. Since it is possible that the heating of the plasma by Alfven waves may be highly inefficient (Lazarian & Vishniac 1999) we expect that typically only a small fraction of the available magnetic energy is observed in SFs. However, these fractions are sufficiently low that it is plausible that the stars' magnetic fields will have configurations with this much energy available for reconnection. Thus, we take the measured high magnetic field on two-out-of-two SF stars to represent a successful prediction of our model as well as to demonstrate that the energy available within our model accounts for the observed energetics of superflares.

Gray (1984) notes that π^1 UMa is unique in his sample of being an early type star with

a high magnetic field. This unusual presence of a high field provides a distinct peculiarity between SF stars and other normal solar-type stars. The existence of this peculiarity on a SF star also suggests a connection between the high magnetic field and the SF. Our model provides a causal connection between the high magnetic field and the superflare.

What does our model predict for the typical time scales in the SF light curves? One way to make the prediction is by analogy with the RS CVn stars which have time scales from hours to days (Osten & Brown 1999). A second way is to realize that the typical rise times will be of order the time it takes for an Alfven wave to cross the primary emission region. For reconnection events midway between a planet and the star, the characteristic size scale will be ≈ 0.1 AU. However, the bulk of the emission is likely to arise when the Alfven waves encounter dense gas near the star's surface. The characteristic size scale would then be more like a solar radius ($7x10^{10}$ cm). The Alfven velocity can be estimated in the case of the SF on κ Ceti, where the density of the emitting region was $1.6x10^{-10}$ gm/cm^3 (Robinson & Bopp 1988) and the magnetic field is 1500 Gauss (Montesinos & Jordan 1993), so that the Alfven velocity in the emission region is near $3.3x10^7$ cm/s[1]. The crossing time is thus of order 30 minutes, which is comparable to the time scale for the observed superflare on κ Ceti. For weaker magnetic fields, smaller emission regions, or propagation at slower than the Alfven velocity, the rise times and durations can be substantially larger than 30 minutes. Thus, our model predicts rise times and durations from hours to days for SFs, and this is just as observed.

The Alfven waves will accelerate particles to a wide range of energies, with a spectrum that is difficult to predict from first principles. Nevertheless, we expect that SFs will have spectra comparable to those of RS CVn flares and also of solar flares. Thus, we expect that SFs will emit large amounts of x-rays, optical light, and even radio emission. As with solar flares (Foukal 1990; Robinson & Bopp 1988), regions above the star's surface will be heated

to temperatures of > 15000 K to form prominent He I emission lines. So our expected broad range of energies is matched by that observed for superflares, with a prediction that SFs will also be bright at radio frequencies.

This model shares with RS CVn flares all of the essential physics. The substitution of a Jovian planet for the RS CVn's non- or less-active component should not alter these properties since the role of this companion is merely to anchor a magnetic field. As long as the companion has a magnetic dipole moment of adequate strength, the composition and physical size of the companion is not important. Therefore, the energy budget, outburst time-scale, and range of emitted frequencies should be comparable. Thus, we take the RS CVn flares as proof that our SF model satisfies the first three constraints. The fourth constraint, the lack of SFs on our Sun, is also satisfied since our Solar System does not have a planet with a large magnetic dipole moment in a close orbit.

3. Discussion

Our SF model makes two testable predictions. First, we require that SF stars have close-in planets that might be revealed by small radial velocity variations of the primary star. The masses and orbital periods of the planets are not well constrained by our model and the orbital inclination might be near face-on, so some SF stars might easily not have detectable planets by this method. Only one SF star (κ Ceti) has been searched for planets to date, and its radial velocity variations (with a 20 m/s dispersion) allow for a Saturn-mass planet even at low inclination (Marcy private communication). Second, the SF stars must have a sufficient magnetic field to provide the observed flare energy. This would require surface dipole fields of $\sim 6 - 1200$ Gauss should the entire field be annihilated, and proportionally more should only a fraction be annihilated. This prediction has already been partially confirmed by the high magnetic fields on the only two SF stars tested to date.

Within our model, SFs will occur only on solar-type stars with planetary systems, and these are the same systems in which life can form. These planets will be close to the primary, where the flux from the SF will be large and might have profound consequences for formation and survival of extra-terrestrial life; such life might be fundamentally different from terrestial life. These consequences might include the provision of energy needed to initiate biological processes or the destruction of life forms by high radiation levels.

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