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Super Flares in M Stars and Associated Characteristics of Active Regions and Magnetic Fields

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Abstract. Observations of super flare occurrence (with energy 10^{33}–10^{36} erg)s in low mass stars like M dwarfs still remains as a puzzle. In this paper we have inferred the typical sizes and characteristics of magnetic fields associated with active regions in M dwarfs responsible for these super flares. This is done by extrapolation of physical conditions associated with largest solar flares. The average poloidal and toroidal magnetic fields near the surface of selected M dwarfs will be also inferred in this context.

Keywords. Super flares, M dwarfs, Solar flares, Active regions, Magnetic fields

1. Introduction

Solar flares are energetic phenomena in the solar atmosphere with profound influence on the space weather near Earth. The mechanism of solar flares is a plasma phenomena involving reconnection where stored magnetic potential energy in active regions is suddenly converted in to kinetic energy of particles and radiation (involving also enhanced EUV and X ray emission). Eighty percent of stars in our milky way are inferred to be M dwarfs which hosts many extra solar planets. Frequent occurrence of flares with energy with 2–4 orders of magnitude higher than the largest solar flares in M dwarfs (called super flares) is still a puzzle (Howard *et al.* 2020). It will be worthwhile to know the physical conditions and mechanisms associated with the super flare occurrences in M stars In this paper we have carried out order of magnitude calculations of the sizes of active regions and associated magnetic field characteristics related to super flares in M stars.

2. Magnetic fluxes associated with super flares in M stars

We can expect close relations between sizes of active regions and its magnetic field characteristics with the energy of super flares. An upper limit of magnetic flux in an active region on the Sun is found by Livadiotis and Moussas (2009) as 7.23×10^{23} Mx.

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From solar observations the maximum total magnetic flux in sunspots is found to be 3.18×10^{23} Mx. This is found to be associated with maximum area of sunspots during the past 300 years and observed in 1947. The upper limit to active region flux in the Sun is expected to be connected with maximum energy of solar flares

It is understood that solar flare energy is related to energy stored in magnetic fields of active regions in the Sun (Mayfield and Lawrence 1985). In this connection we can expect a relation between solar flare energy (Ef) and total magnetic flux (Fm) in the active region/active region group associated with the solar flare.

$$Ef = f(Fm) \tag{1}$$

When the solar flare energy is found to vary in the range 10^{24} to 10^{32} ergs, the associated magnetic flux in sunspots/sunspot groups is found to vary in the range 10^{21} to 10^{23} Mx. So we can expect a non-linear relation between Ef and Fm. The energy of super flares in M dwarfs is inferred to vary between 10^{33} to 10^{36} ergs. Then a heuristic inference of associated Fm for the super flares is:

$$Fm = 10^{24} - 10^{25} \text{ Mx} \tag{2}$$

3. Inference of the sizes of active regions related to M dwarf super flares

Sakurai and Toriumi (2023) found the following linear relation between sunspot area (Sa) and associated total magnetic flux (Φ_S) based on relevant observations:

$$\text{Log}(\Phi_S) = \text{Log}(Sa) - 19.7 \tag{3}$$

Here Φ_S is expressed in units of Mx and area Sa in units of msh (millionth of the solar hemisphere)

If we assume that the relation (3) is also valid for stellar flares then we can find the area of active regions responsible for super flares in M stars

$$\text{For } \Phi_S = 10^{24} \text{ Mx we find that } Sa = 1.995 \times 10^4 \text{ MSH} \tag{4a}$$

$$\text{For } \Phi_S = 10^{25} \text{ Mx we find that } Sa = 1.995 \times 10^5 \text{ MSH} \tag{4b}$$

For $\Phi = 10^{24}$ Mx,

$$\text{we have found } S \text{ (super flares) } = 1.995 \times 10^4 \text{ MSH} = 0.02 \text{ As} \tag{5}$$

Here As is the area of solar hemisphere or disc.

For $\Phi = 10^{25}$ Mx,

$$\text{we have found } S \text{ (super flares) } = 1.995 \times 10^5 \text{ MSH} = 0.2 \text{ As} \tag{6}$$

Our calculations of S are agreement with similar values reported in published literature (Herbst *et al.* 2021). Validity of these results will also depend on the radius of M stars relative to Sun under consideration.

4. Inference of magnetic field strengths in the active regions associated with M dwarf Super Flares

The maximum magnetic field strength in active regions associated with super flares in M stars can be inferred from different methods:

4.1. *Calculations based on Flare energy*

It is understood that energy of the super flares in solar/stellar flares (E_f) is equal to the energy stored magnetic fields ($B^2/4\,\pi$) in the active regions associated with these flares

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This implies that

$$E_f = B^2/4\pi \tag{7}$$

Here B is the magnetic field strength in the solar/stellar active regions.

$$\text{We infer } B \text{ (solar)} = 4 \text{ kG for extreme solar flares.} \tag{8}$$

The energy of extreme flares can be assumed as

$$Ef(\text{Sun}) = 10^{32} \text{ ergs}, Ef(M \text{ dwar}) = 10^{36} \text{ ergs} \tag{9}$$

We can find that field strength B of active regions responsible for extreme super flares as

$$B(M \text{ star}) = 200 \text{ kG} \tag{10}$$

4.2. *Calculations based on internal magnetic fields of the stars*

The toroidal magnetic fields related to active regions on the stellar surface is connected to the toroidal fields in the interior or these stars. The toroidal magnetic fields in the base of solar convective zone is inferred to be of the order of 10^5 G or 0.1 MG (Fan 2021). From a recent study (Feiden and Chaboyer 2014) related to low mass star magnetic field generation, the field strength of toroidal fields in the interior of such stars (including M dwarfs) is inferred to be of the order of 10 MG or 10^7 G. This implies that toroidal fields in M stars can be 100 times more stronger than the same for Sun.

4.3. *Inference of poloidal and toroidal magnetic fields for selected M dwarfs*

In the case of the Sun poloidal fields in the sun of few Gauss in intensity is amplified by differential rotation to form toroidal fields in active regions in the photosphere of the order of few kG in intensity. The poloidal to toroidal field amplification factor for the Sun (Af) is of the order of 1000.

Remote measurements of magnetic fields in many M dwarfs (Kochukov 2021) suggest the presence of strong poloidal magnetic fields of the order of few kG. This implies that toroidal fields in these stars related to active regions are likely to be several orders stronger. As per the results in 4.1 and 4.2, poloidal to toroidal magnetic flux amplification factor for M stars can be inferred to be close to hundred. The inferred surface magnetic fields in M stars is likely to be poloidal or large scale magnetic fields (Bp) The toroidal field strength (Bt) in such stars is suggested to be given by the following relation:

$$Bt = Af \text{ Bp} = 100 \text{ Bp} \tag{11}$$

In Table 1 we have given poloidal fields of selected M stars from published values of surface fields included in the study of Kochukov (2021) inferred from a model involving stokes spectra of these stars. The average toroidal field strength related to active regions near the surface of these stars given in this table is estimated using relation (11).

5. Discussion

The magnitude of solar/stellar flare energy reflects the characteristics of active regions and associated magnetic fields responsible for these flares. Naturally superflares in M dwarfs are associated with very large active regions and super-strong magnetic fields whose details are worked out in this paper. We have inferred the magnitudes of poloidal and toroidal magnetic fields in selected M dwarfs whose surface magnetic fields details are reported in literature. The inferred values of poloidal and toridal magnetic fields for Trappist-1 by Mullan *et al.* (2018) supports our calculations given in Table 1. To account

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Table 1. Average poloidal and toroidal magnetic field strengths near the surface of selected M dwarfs. Poloidal field values are derived from observations (after Kochukov 2021). Toroidal field values associated with active regions in these stars are inferred assuming a fixed poloidal to toroidal flux amplification factor ($Af = 100$).

Name of the M star	Poloidal magnetic field (kG)	Estimated mean toroidal magnetic field (kG)
GJ 2005A	2	200
GJ 65B	6.7	670
GJ 278Cb	3.2	300
GJ 412B	7.3	730
GJ 3622	1.4	140
GJ 3059	4.1	410

for the emergence of magnetic fields near the surface of M dwarfs which is two orders of magnitude higher than the solar magnetic fields, a dynamo quite different from that of our Sun may exist inside these low mass stars.

Conclusions

(1) We have made heuristic inferences of the values of active region sizes and magnetic field characteristics (field strength and total magnetic flux) associated super flares in M dwarf stars. Our results are found to be several orders of magnitude greater than the same reported for solar active regions related to large solar flares.

(2) The physical conditions and mechanisms in M stars responsible for the generation of very large active regions and super-strong magnetic fields need detailed investigations. The average poloidal and toroidal magnetic fields generated by the M dwarf dynamo is inferred to be at least hundred times stronger than the magnetic fields generated by the solar dynamo.

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