Presented at the
11th Workshop on Cool Stars,
Stellar Systems and the Sun
Tenerife, Oct 4 - 8, 1999

PSI-PR-99-27-D

Deep Radio Observations of Young Solar Analogs

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Abstract. We discuss recent deep VLA observations of solar analogs and derive upper limits to the filling factors of hot plasma enclosed in strong magnetic fields and to wind mass loss over the solar main-sequence life. We discuss the importance of rotation for the radio emission level.

1. Introduction

Solar-type stars of different ages are important objects for tests of stellar evolution theory and for understanding the past of our own Sun. Much of the solar atmosphere (and by implication of solar-analog stellar atmospheres) is controlled by magnetic fields, and these are generated by the internal dynamo process. The rotation period $P_{\rm rot}$ of solar-type main-sequence stars converges, for ages exceeding approximately 200–300 Myr, to a unique value determined by $P_{\rm rot}$ only (to within about 10%; Soderblom et al. 1993). As the observable magnetic activity indicators also very strongly depend on $P_{\rm rot}$, we can conveniently study the probable solar past (at ages beyond 200–300 Myr) by using solar analogs with known ages.

Various coronal activity indicators decay with age: i) The X-ray luminosity of solar analogs (below the saturation regime) depends on rotation as $L_{\rm X} \propto P_{\rm rot}^{-2.6}$ (Güdel et al. 1997) and therefore on age as $L_{\rm X} \propto t^{-1.3}$ since $P_{\rm rot} \propto t^{1/2}$ (Skumanich 1975). ii) The luminosity of non-thermal gyrosynchrotron emission also decays, perhaps much faster as it is not significantly detected on the present-day Sun except during flares. iii) The average coronal non-flaring temperature decays with age roughly as $t^{-0.3}$ (Güdel et al. 1997).

Thermal free-free radio emission predominantly stems from the level where the optical depth $\tau = 1$, i.e., from chromospheric levels with $T \approx (1-2) \times 10^4$ K (Gary, Zirin, & Hurford 1990). Thermal gyroresonance emission originates from hot coronal plasma trapped in strong magnetic fields, also typically from the level where $\tau = 1$. The observed emission can provide information on the filling factors of such material (Güdel & Benz 1989; White, Lim, & Kundu 1995). Gyrosynchrotron emission, observed to be optically thin or thick, originates from high-energy electrons trapped in magnetic loops. Finally, (partly) ionized winds emit a characteristic spectrum of radio emission dependent on the mass loss and the outflow velocity (e.g., Wright & Barlow 1975).

Mass loss may be relevant to the paradox of the faint young Sun, an outstanding problem in the study of the early planetary climates. Standard stellar evolution theory predicts that the solar luminosity at the beginning of the Archean eon (3.8 Gyrs) was approximately 75% of its present value (Gough 1981). The lower insolation at the distances of Earth and Mars should have resulted *in surface temperatures below 0° C*, in conflict with an interpretation of the geological records on both planets which holds that warmer temperatures and liquid water were present at the surface (Sagan & Mullen 1972; Karhu & Epstein 1986). Elevated levels of greenhouse gases may have maintained surface temperatures above freezing on the early Earth and Mars (Kasting & Grinspoon 1991).

Alternatively, a sufficiently high mass loss rate from the young Sun would imply that the radiative flux in the upper terrestrial atmosphere was higher for two reasons: i) The luminosity of a young (near-ZAMS) star is a sensitive function of its total mass: $L \propto M^4$ and therefore $\mathrm{d}(\log L) \approx 4\mathrm{d}(\log M)$. ii) Conservation of the Earth's orbit angular momentum would impel the expansion of its orbit in time, implying a smaller distance to the young Sun.

2. New observations

Previous surveys of solar (G type) analogs have reached the 10–20μJy level (1σ; Güdel et al. 1995, 1998b, Table 1; Whitmire et al. 1995). Most detections appear to be from very young stars (<200 Myrs) with the exception of apparently peculiar sources at ages beyond 1 Gyr (Güdel et al. 1995). Except from the also peculiar F0+G4 V binary 71 Tau, no definite detection has been reported for the age range between 200–1000 Gyr, with deep upper limits given by Güdel et al. (1998b). We will briefly revisit these results and add a new and deeper continuum observation of π^1 UMa obtained with the NRAO VLA in its A array configuration on February 14 and 15, 1999, at a frequency of 8.4 GHz. The 12.2 hrs on source resulted in a 1σ rms value of 6.4 μJy. No source was detected. Table 1 presents an update of detected G (and F) stars and deep upper limits. We will discuss implications from the upper limits for the intermediate-age solar analogs π^1 UMa, κ^1 Cet, and β Com.

3. Free-free emission?

Using the Rayleigh-Jeans approximation for the flux density S

$$S = \frac{2kT\tau\nu^2}{c^2}\frac{\pi R^2}{d^2} \approx 0.049\left(\frac{T}{10^6\ \mathrm{K}}\right)\left(\frac{\nu}{1\ \mathrm{GHz}}\right)^2\left(\frac{R}{R_\odot}\right)^2\left(\frac{1\ \mathrm{pc}}{d}\right)^2 \tau\ \mathrm{mJy} \quad (1)$$

(R = source radius, T = electron temperature, d = stellar distance, k = Boltzmann constant, ν = observing frequency, τ = optical depth), we find for optically thick chromospheric emission (with $\tau = 1, T = 1.5 \times 10^4$ K, $\nu = 8.4$ GHz)

$$S \approx \frac{0.05}{d_{\mathrm{pc}}^2}\ \mathrm{mJy}. \quad (2)$$

This result is compatible with solar measurements and indicates that all chromospheric emission is a factor of ≈30 below our detection limits.

Table 1. Quiescent F and G IV-V radio stars and estimated ages

Star	HD number	Spectral Type	d (pc)	$\log(L_X)$ (erg/s)	$\log(L_X/L_{bol})$	$\log(L_R)$ (erg/s/Hz)	Age (Myr)	Ref[a]
47 Cas B	12230	G0-5V?	33.54	30.31	-3.3?	14.91	~70	2
EK Dra	129333	G0V	33.94	29.93	-3.6	14.18	~70	1
HII 1136	...	G8V	130	30.14	-3.0	15.50	~70	3, 4
Gl 755	181321	G5V	20.86	29.48	-4.1	13.99	~200	1
π^1 UMa	72905	G1V	14.27	29.10	-4.5	<12.67	~300	10
α Crv	105452	F0IV-V	14.77	29.41	-4.8	13.72	~300	1
71 Tau	28052	F0V+G4V	47.9	30.23	-4.8	14.66	~600	7, 6
κ^1 Cet	20630	G5V	9.16	28.79	-4.7	<12.42	~700	5
β Com	114710	G0V	9.15	28.21	-5.5	<12.53	~1500	5
κ For	14802	G1V	21.93	29.40	-4.7	14.16	~1800	1
Gl 732.1	175225	G9IVa	26.10	29.48	-4.7	14.14	~3600	1
α For	20010	G8V(+F8IV)	14.11	29.64	-4.6	14.17	~5000	1
Procyon	61421	F5IV-V	3.50	27.23	-7.2	11.70	...	8, 9
HR 9107	225239	G2V	36.80	29.76	-4.4	14.47	~8000	1

[a]References: (1) Güdel, Schmitt, & Benz 1995; (2) Güdel et al. 1998a; (3) Lim & White 1995; (4) X-rays: Stauffer et al. 1994; (5) Güdel, Guinan, & Skinner 1998b; (6) Stern et al. 1992; (7) Güdel et al. 1996; (8) X-rays: Jordan et al. 1986; (9) Drake et al. 1993; (10) this paper. Distances from ESA 1997

Optically thin free-free emission from the hot, X-ray emitting plasma in coronal loops can be estimated as follows: The radio optical depth is

$$\tau = \int \kappa \mathrm{d}l \approx \frac{0.16}{\nu^2 T^{3/2}} \int n^2 \mathrm{d}l \tag{3}$$

and the X-ray volume emission measure EM, using a filling factor f in the approximation of a small coronal height,

$$\mathrm{EM_X} = 2\pi R^2 f \int n^2 \mathrm{d}l. \tag{4}$$

For plasma between 2–8 MK (typical for our targets), the EM can be estimated from the X-ray luminosity L_X with a conversion factor $\alpha(T)$ (Mewe et al. 1985):

$$L_X = \alpha(T)\mathrm{EM_X} \approx (10^{-22} - 3.5 \times 10^{-23})\mathrm{EM_X} \quad [\mathrm{erg\ s^{-1}}] \tag{5}$$

Thus, from equations (1), (3)–(5), we find (using $T_{\mathrm{MK}} = T/(10^6\ \mathrm{K})$)

$$S = 2.6 \times 10^{-52} \frac{L_X}{\alpha(T) T_{\mathrm{MK}}^{1/2} f d_{\mathrm{pc}}^2}\ \mathrm{mJy} \approx (1.8 - 3.3) \times 10^{-30} \frac{L_X}{f d_{\mathrm{pc}}^2}\ \mathrm{mJy}. \tag{6}$$

For our three targets, we find values not exceeding 2μJy even for the hotter temperatures and $f = 1$. Any bremsstrahlung contribution is beyond reach even for our deep integrations.

4. Gyroresonance emission

Gyroresonance emission is a tracer of hot plasma trapped in low-lying strong magnetic fields (e.g., Güdel & Benz 1989; White et al. 1995) since kG magnetic

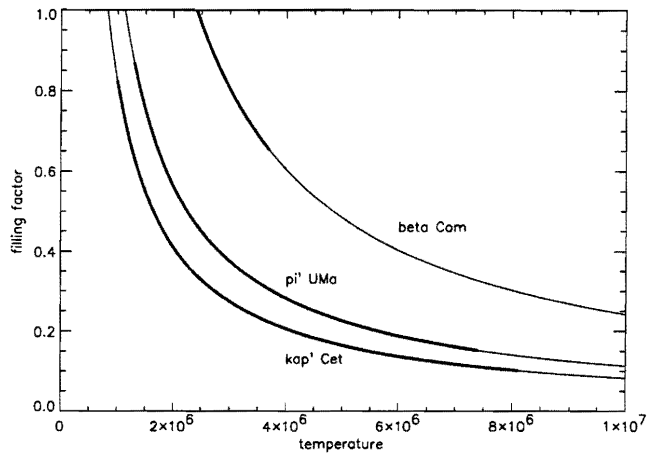

Figure 1. Upper limits for filling factor of the low corona as a function of temperature; thick lines refer to the range of measured coronal temperatures (Güdel et al. 1997; Drake et al. 1994).

fields and coronal temperatures are required to make the emission optically thick. We use Eqn. (1) to find (for S in mJy)

$$f \approx 20.4 \frac{S d_{\rm pc}^2}{T_{\rm MK} \nu_{\rm GHz}^2} \tag{7}$$

which provides interesting limits to the filling factor f as a function of the plasma temperature, as illustrated in Figure 1. If the 8.4 GHz emission is optically thick at the suggested coronal temperatures, then the coronal filling factor, at least at low heights, is significantly below unity for the three non-detections.

5. Stellar mass loss?

A spherically symmetric stellar wind with density falling as r^{-2} from a star at a distance d will have the flux density spectrum (Wright & Barlow 1975)

$$S_w = 60 \left(\frac{\dot{M}}{10^{-10} M_\odot {\rm yr}^{-1}} \right)^{4/3} \left(\frac{\lambda}{3.6 \text{ cm}} \right)^{-2/3} \left(\frac{d}{10 \text{ pc}} \right)^{-2} \quad \mu{\rm Jy} \tag{8}$$

Our detection limit for π^1 UMa corresponds to a mass loss of $5 \times 10^{-11} M_\odot {\rm yr}^{-1}$. Since a magnetized wind transports away angular momentum from the star, the rotation rate decreases. Empirically, $P_{\rm rot} \sim t^{1/2}$ (Skumanich 1972). Gaidos, Güdel, & Blake (1999) argue that $M \propto P_{\rm rot}^{-\alpha}$ with $\alpha \ll 1$. Thus, $\dot{M}$ will show a power-law evolution in time as well; we show in Figure 2 the mass loss evolution for a total loss of 3% and 7%, along with the constraints for the three non-detections and the modern Sun. We can therefore rule out mass loss greater than 7% in the context of this model.

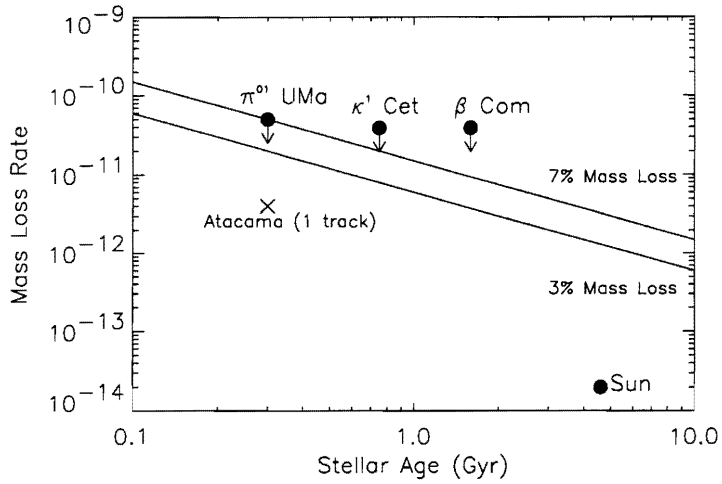

Figure 2. Upper limits for total mass loss (Gaidos et al. 1999).

6. Rotation and Activity

For a subsample of solar analogs, sufficient rotational and radio data exist for further conclusions on the evolution of the radio behavior. Fig. 3 shows $L_R/L_{\rm bol}$ values and upper limits for a sample of solar analogs, including RS CVn-like pairs of identical GV stars (BI Cet, ER Vul, TZ CrB; Drake, Simon, & Linsky 1989). Beyond the saturation limit (around $P_{\rm rot} \approx 2$ d), radio emission drops rapidly - in fact much more rapidly than found for X-rays. Since the *detected* stars show signatures of non-thermal emission, Fig. 3 provides evidence for a rapid decay of the production of accelerated particles in the aging stellar coronae.

Acknowledgments. NRAO is a facility of the US National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

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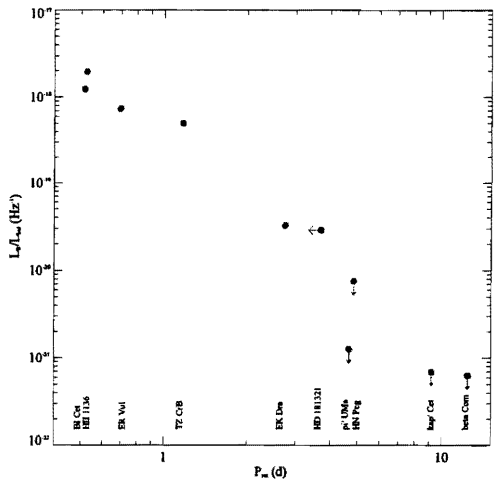

Figure 3. Radio luminosity L_R (at 8.4 GHz) vs. P_{rot} for G stars.

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