The Radio Properties of the dMe Flare Star Proxima Centauri

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ABSTRACT

We present radio observations of the dM5.5e flare star Proxima Centauri at 20, 13, 6, and 3.5 cm. The star was only detected during an impulsive, highly circularly–polarized and apparently narrowband flare at 20 cm, similar to those seen on other dMe flare stars. This flare was detected in just ∼1.7 hrs of observing time spanning a ∼12 hr period, suggesting that Proxima Centauri may be a prolific producer of coherent bursts at 20 cm. On the other hand, despite ∼30 hrs of observing time at both 6 and 3.5 cm over a 4 yr period, the star was not detected as either a flaring or a quasi–steady (quiescent) source at these wavelengths. We place an upper limit of $\sim 2 \times 10^{11}$ erg $\mathrm{Hz^{-1}\ s^{-1}}$ on its radio luminosity at 6 and 3.5 cm, the lowest detection threshold yet reached for a star other than the Sun. This upper limit is approximately equal to the radio luminosity of the active Sun (i.e., at or close to the peak in its activity cycle) outside of flares.

Our results place important constraints on the filling factor of ∼500—1000 G magnetic loops containing X–ray–emitting plasma on Proxima Centauri. Because such loops should be optically thick to gyroresonance emission at cm wavelengths, their filling factor can be inferred directly from the measured stellar radio flux density. Our radio results imply that loops at temperatures $\sim 2 \times 10^7$ K, representative of the hot stellar X–ray component, have a filling factor of $\leq 13\%$. Loops at temperatures $\sim 3 \times 10^6$ K, similar in temperature to the non–flaring solar active region corona, have a filling factor of $\leq 88\%$. Our results are compatible with present empirical relationships for the magnetic field parameters of late–type dwarf stars as applied to Proxima Centauri. Based on its measured rotation period ($P_{rot} \approx 41$ days) and the ratio of its soft X–ray to bolometric luminosity ($L_x/L_{bol} \approx 2.4 \times 10^{-4}$), these relationships predict that Proxima Centauri should be about an order of magnitude below the saturation limit in magnetic activity, where the entire surface of stars is thought to be covered by kilogauss X–ray loops. We compare our results with the contrasting case of UV Ceti, a dM5.5e flare star that according to the same empirical relationships should be approximately as magnetically active as Proxima Centauri. UV Ceti, however, displays quiescent radio emission with a luminosity that is more than an order of magnitude higher than the upper limit placed on Proxima Centauri.

Our radio observations place an upper limit of $\sim 7 \times 10^{-12}$ $M_\odot$ yr^{-1} on the mass–loss rate by any stellar wind (assumed to have a velocity of 300 km s^{-1}) from Proxima Centauri. This upper limit is almost 2 orders of magnitude lower than that inferred by Mullan et al. (1992) from mm wavelength observations of other dMe flare stars. We show that the high mass–loss rate inferred by Mullan et al. (1992) is untenable if our present understanding of the cm wavelength radio emission of dMe flare stars is correct.

Subject headings: stars: individual: Proxima Centauri - radio continuum: stars stars:activity - stars: coronae - stars: magnetic fields - stars: mass loss

1. INTRODUCTION

By analogy with the Sun, the coronae of late–type dwarf stars are thought to consist of closed magnetic fields confining hot plasma (hereafter referred to as magnetic loops; e.g., Rosner, Golub, & Vaiana 1985). Because, apart from the Sun, the coronae of these stars cannot be spatially resolved, any knowledge of the distribution in field strength, plasma density, and temperature of magnetic loops over the stellar surface has to be inferred indirectly. In this paper we present radio observations which probe the corona of Proxima Centauri, the star closest to the Sun. These radio data, when combined with published soft X–ray observations, place important constraints on the properties of coronal magnetic loops on a dMe flare star.

White, Lim, & Kundu (1994; hereafter WLK94) have shown how radio and soft X–ray data can be used together to test coronal models for solar–type stars. As is the case in the solar corona, magnetized X–ray loops on these stars should be optically thick to gyroresonance radio emission up to a turnover frequency (in GHz)

$$\nu_{t,GHz} = 2.8 \times 10^{-3} \ s \ B_{max} \quad , \tag{1}$$

where the particular harmonic s (an integer) is the highest at which the emission is optically thick, and B_{max} the maximum field strength of the loop in gauss. The turnover frequency of gyroresonance emission, as on the Sun, is expected to depend primarily on B_{max}. On rapidly–rotating late–type dwarf stars, much of the photosphere is thought to be covered by kilogauss magnetic fields (see reviews by Saar 1990a, 1990b, and references therein); in this situation the magnetic field cannot diverge quickly with height, and hence the magnetic scale height in the corona is expected to be large (see discussion in WLK94). Simple theory then predicts that, for parameters typical of dMe stars, gyroresonance emission should be optically thick at microwave frequencies for all harmonics up to $s = 5$ (WLK94). (By comparison, on the Sun gyroresonance emission is throught to be optically thick up to only $s = 2$ or $s = 3$.) Thus, at a radio frequency of, say, 15.0 GHz, loops with magnetic field strengths $B \geq 1070$ G should be optically thick to gyroresonance emission, and have radio brightness temperature equal to the soft X–ray temperature of the confined plasma. Measurement of the stellar radio flux then gives a direct measure of the projected surface area coverage (i.e., projected filling factor; the ratio of the projected area of emission to the area of the stellar disk) of such loops. WLK94 used this technique to probe the filling factor of loops with kilogauss fields ($B \geq 1070$ G) confining hot plasma ($T \geq 10^7$ K) on numerous highly active dMe flare stars. They found that in the majority of cases — specifically where the radio emission is not confused by nonthermal radio emission — the upper limit placed on the filling factor of any such loops can be much smaller than the stellar disk.

In this paper, we use the same technique to probe the properties of X–ray–emitting coronal magnetic loops on the dM5e flare star Proxima Centauri. Its proximity allows us to probe with great effective sensitivity its radio corona. Specifically, we are able to investigate loops with field strengths of only 400–600 G, and for these loops determine not only the surface coverage of those confining relatively hot X–ray–emitting plasma at $T \geq 10^7$ K, but also those containing cooler X–ray–emitting plasma at $T \approx 3 \times 10^6$ K. The latter is comparable in temperature to the non–flaring (i.e., quiescent) solar active region corona. In §2 we present our radio observations and results. In §3 we briefly summarize previously published soft X–ray observations of Proxima Centauri, and also the distribution in emission measure with temperature that has been inferred for its quiescent X–ray corona. In §4 we use the radio and X–ray data together to constrain the properties of coronal magnetic loops on Proxima Centauri, and in §5 we discuss our results in the context of our present understanding of the radio emission and magnetic field parameters of active late–type dwarf stars. Finally, in §6 we summarize our conclusions.

2. OBSERVATIONS and RESULTS

Sensitive radio observations of Proxima Centauri became possible with the commissioning of the Australia Telescope Compact Array (ATCA) in the late 19080s. We observed Proxima Centauri with ATCA on four occasions spanning a period of nearly 4 years. The dates, times, and wavelengths at which these observations were performed are summarized in Table 1. On 1990 July 24, we observed the star at 6 cm only. On 1991 Aug 31, we switched consecutively between 20, 13, 6, and 3.5 cm. On 1993 Sep 16 and 1994 May 25, we observed simultaneously at 6 and 3.5 cm. In the first observation no polarization measurements were made, and here we calibrated the data using AIPS. In all subsequent observations polarization measurements were carried out, and thence we calibrated the data using MIRIAD. In all observations we imaged the data using AIPS.

The results of our radio observations are summarized in Table 1, where the upper limits quoted are 3σ, with σ the noise level in the integrated data at a given wavelength. We detected Proxima Centauri only once, on 1991 Aug 31, when it displayed a short duration and highly circularly–polarized ($\sim$100%) flare at 20 cm. The temporal morphology of this flare in Stokes I and V is shown in Figure 1. We appeared to have caught the flare only at its peak and/or in its decay phase. It was not detected in the preceding scan at 13 cm, nor in the following scan at 3.5 cm, suggesting that it is narrowband. Apart from this flare, we did not detect the star at any wavelength on the same day, nor on the other days.

Proxima Centauri has a large proper motion, and its optical position listed in widely used catalogues can differ considerably. In Table 2 we list the optical position for Proxima Centauri at equinox 2000 from the SIMBAD database, the Hipparchos input catalog (HIC), and the recent measurement made by Benedict et al. (1993). We also list the proper motion quoted in the SIMBAD database and the HIC. The stellar position listed in the SIMBAD database is quite different from that listed in the HIC and the measurement of Benedict et al. (1993); the latter two positions, on the other hand, agree to within $\sim$1$''$. The position quoted by Benedict et al. (1993) was based on observations made in 1992 Jun/Jul, and corrected for proper motion. The proper motion used, however, was not specified. In this paper we have used the optical position quoted by Benedict et al. (1993), and the proper motion quoted in the Hipparchos input catalog, to derive the optical position of Proxima Centauri during each of our observations.

In Figure 2 we show maps of Proxima Centauri in both Stokes I and V made from the flare at 20 cm on 1991 Aug 31, and the extrapolated stellar optical position. The good agreement between the radio and optical positions (certainly better than $\pm2''.5$, the arm lengths of the cross) suggests that the method used to infer the stellar optical position is reliable. Except for this flare, we did not detect a radio peak greater than 3σ in a circular area of diameter $5''$ (a conservative choice) centered on the optical position of Proxima Centauri in any of our observations. As an example, in Figure 3 we show our most sensitive map at 3.5 cm made from the last observation in 1994 May 25. In all our observations, we determined the noise level at each wavelength from the Stokes V map, except in the first observation when we measured the rms noise level from the Stokes I map at a position far outside the primary beam. Both methods give us a conservative estimate of the actual noise level in each map.

3. SOFT X–RAY EMISSION FROM PROXIMA CENTAURI

There is a long history of soft X–ray observations of Proxima Centauri, beginning in 1979. It has been detected, both in quiescence and in flares, by the X–ray satellites *EINSTEIN* (Haisch & Linsky 1980; Haisch et al. 1980, 1981; 1983; Agrawal, Rao, & Sreekantan 1986; Reale et al. 1988; Schmitt et al. 1990), *EXOSAT* (Collura, Pasquini, & Schmitt 1988; Pallavicini, Tagliaferri, & Stella 1990), and *ROSAT* (Fleming et al. 1993). In Table 3 we summarize all published soft X–ray observations of this star, listing the dates of the observations, the satellite observatory involved, the measured quiescent stellar X–ray luminosity, and the relevant reference(s) for each observation. Over the 11 yr period of reported observations, Proxima Centauri has shown a nearly constant quiescent X–ray luminosity of $L_x \approx 1.5 \times 10^{27}$ erg Hz^{-1} s^{-1}, except on 1980 Aug 20 when it appeared to be a factor of $\sim$2 lower in luminosity than on the other occasions. Collura, Pasquini, & Schmitt (1988) have searched for low–level variability in the quiescent X–ray luminosity of Proxima Centauri, and found none with amplitude greater than 11%–22% on time scales of 67 mins down to 2 mins.

For our purposes the distribution of emission measure with temperature in the corona of Prox Cen is important. The nature of this distribution in the coronae of active late–type dwarf stars has been (and continues to be) a subject of considerable debate (see reviews by Schmitt 1988, and Pallavicini 1988, 1989). There is general agreement that the coronae of these stars cannot be satisfactorily modelled by a single isothermal plasma. Two–temperature and powerlaw differential emission measure (DEM) distributions have also been used as approximations to the true continuous DEM; in general, the two–temperature models seem to give acceptable fits (e.g., Schmitt et al. 1990 and references therein). Recent EUVE observations in which lines from many different ionization states of Fe may be resolved, and which are therefore more appropriate for determining a continuous DEM, suggest that the DEM for active stars is indeed concentrated in two temperature ranges (e.g., Rucinski et al. 1995). We will therefore follow other authors in adopting the two-temperature models as reasonable approximations to the true DEMs. For Proxima Centauri, Schmitt et al. (1990) derived a temperature of $\sim 3 \times 10^6$ K for the cooler X–ray component, and a temperature of $\sim 2 \times 10^7$ K for the hotter X–ray component. As on most other dMe flare stars the hotter component has a larger emission measure than the cooler component, in the case of Proxima Centauri about a factor of 3.5 times larger. In the following we shall use the above temperatures as representative of the temperatures of the two most abundant X–ray–emitting components in the stellar corona.

4. CONSTRAINTS ON PROPERTIES OF CORONAL MAGNETIC LOOPS

At a distance of 1.31 pc, the flux density in μJy, $S_{\mu Jy}$, of a collection of sources, i, with brightness temperature $T_{b,i}$ and projected surface area coverage or projected filling factor, $f_{p,i}$, on Proxima Centauri is given by

$$S_{\mu Jy} = 5.6 \times 10^{-4} \ \lambda_{cm}^{-2} \ \sum_i (f_{p,i} \ T_{b,i}) \quad , \tag{2}$$

where λ_{cm} is the observing wavelength in cm; we have assumed a stellar radius of $0.15 R_\odot$ (Pettersen 1980). Note that $f_{p,i}$ has been defined as the ratio of the actual projected area of emission to the area of the stellar disk, and may therefore be greater than unity. The most stringent constraints on the filling factor of X–ray magnetic loops on this star is placed by the most sensitive observation, that of 1994 May 25, when we place 3σ upper limits of $S_{6cm} \leq 110$ μJy and $S_{3.5cm} \leq 120$ μJy.

As discussed by White et al. (1994), a simple model for the coronae of flare stars which follows from the high filling fraction of strong magnetic fields in the photospheres of these stars is to assume that the X–ray emitting plasma is confined in coronal loops with strong magnetic fields. For typical conditions in flare star coronae, the hot component of the coronal plasma will be sufficiently hot and dense that such loops will be optically thick to gyroresonance emission at wavelengths of 6 and 3.6 cm as long as the field strength exceeds 430 and 610 G, respectively (corresponding to a gyroresonance harmonic of s=5). Proxima Centauri has X–ray properties very similar to those of UV Ceti (see below), which is one of the examples used by WLK94, and so the arguments used for it may be applied to Prox Cen also. Our radio data place stringent constraints on the (solid angle) filling factor of loops with such strong magnetic fields containing hot X–ray emitting plasma at a (representative) temperature of $\sim 2 \times 10^7$ K. The measured 6 cm upper limit implies that any such loops must have $f_p < 0.35$, whereas the 3.5 cm upper limit implies that any corresponding loops must have $f_p < 0.13$. These limits are comparable to or smaller than those inferred by WLK94 for other dMe flare stars, with the important difference being that — for the same filling factor of strong photospheric magnetic fields — the loops considered here are permitted to have significantly lower (maximum) field strengths. The radio data also place constraints on the filling factor of X–ray–emitting loops with a temperature of $\sim 3 \times 10^6$ K, similar in temperature to the solar active region corona. Because these loops are cooler, they will not be optically thick up to s=5; rather, they are only likely to be optically thick up to s=3, corresponding to minimum magnetic field strengths of 730 G at 6 cm and 1040 G at 3.5 cm wavelength. The 6 cm upper limit implies that any such optically thick loops must have $f_p < 2.36$; the 3.5 cm data place a more stringent upper limit, implying that any loops with sufficient field strengths must have $f_p < 0.88$. Given the likely finite spread in temperature of the cooler X–ray component, our results are compatible with a filling factor of strong loops containing this cooler coronal component of approximately unity. These results are summarized in Table 4. Note that in deriving the above constraints we have considered each X–ray component separately; when considered together, the upper limits placed on the filling factor are even smaller than those derived above.

Alternatively, we can consider the upper limit placed by our radio results on the (uniform or average) stellar disk temperature, T_{disk}. Our results imply that $T_{disk} \leq 7.1 \times 10^6$ K at 6 cm, and $T_{disk} \leq 2.6 \times 10^6$ K at 3.5 cm. These upper limits are higher than the temperatures in the stellar chromosphere and transition region. They clearly indicate that the lower corona of Proxima Centauri cannot be filled with magnetic loops of kilogauss magnetic field strengths and containing X–ray–emitting plasma with temperatures significantly above that of the active solar corona. Two other models would be consistent with the data: a corona in which the coronal loops with field strengths in excess of 400 G do contain hot coronal plasma but their filling factor is small; or else a corona in which the filling factor of loops with large field strength may be high, but the hot coronal plasma lies in loops with low magnetic field strengths, e.g., at large heights in the corona. The latter explanation was preferred by WLK94 for the results in their sample of very active stars. As we discuss below, indirect evidence argues in favor of the former explanation in the case of Prox Cen.

5. DISCUSSION

5.1. Comparison to other dMe flare stars

At present, the dMe flare stars Proxima Centauri and the binary system L726–8 containing UV Ceti, the prototype flare star, are the latest–spectral–type M dwarfs that have been well studied in both radio and soft X–rays. Proxima Centauri and UV Ceti have almost identical spectral types, near M5.5, and also almost identical soft X–ray luminosities (e.g., Agrawal et al. 1986; Collura et al. 1988; Fleming et al. 1994). Note that the components of the L726–8 system are generally not spatially resolved in soft X–ray observations, and the soft X–ray luminosity quoted in the literature for UV Ceti often refers to the total luminosity of the system. Because the primary component of the L726–8 system, L726–8A, is only slightly earlier in spectra class (M5) than UV Ceti, both companion stars are thought to have approximately equal soft X–ray luminosities. Under this assumption, UV Ceti has a soft X–ray luminosity equal to or no more than a factor of 2 higher than (depending on the reference used) that of Proxima Centauri. Despite their similar spectral classes and soft X–ray luminosities, outside of flares the upper limit placed on the radio luminosity of Proxima Centauri is at least a factor of 40–80 lower than the quiescent luminosity of UV Ceti. The latter is always detectable as a quasi–steady source with a flux density of 1–2 mJy at cm wavelengths, and is considered to be the prototypical quiescent stellar radio source (see White, Kundu, & Jackson 1989 and references therein).

Our result again emphasizes the unusually high radio luminosity of UV Ceti. By comparison, its binary companion L726–8A is usually only detected as an impulsive flaring source (Gary, Linsky, & Dulk 1982; Kundu & Shevgaonkar 1985; White, Kundu, & Jackson; Kundu et al. 1987; Jackson, Kundu, & White 1989). When detected as an apparently slowly–varying source, it usually has a flux density of 0.3–0.6 mJy at 6 and 3.6 cm (Kundu & Shevgaonkar 1985; Kundu et al. 1987; Güdel & Benz 1989), although flux densities ≥ 1 mJy (Gary, Linsky, & Dulk 1982; Jackson et al. 1989) and upper limits ≤ 0.3 mJy (Linsky & Gary 1983; Güdel & Benz 1989) also have been obtained. Thus, outside of flares, and when detectable as a slowly–varying source, the luminosity of L726–8A is typically a factor of $\sim$3 lower than the quiescent luminosity of UV Ceti. Most importantly, however, L726–8A does not appear to display quiescent emission with the same steady nature as that seen on its companion UV Ceti (or, if it does, at a much lower luminosity than presently detectable), despite having almost identical physical paramaters.

The unusually high radio luminosity of UV Ceti also has been noted by Güdel et al. (1993) from the point of view of a proposed correlation between the soft X–ray and microwave luminosity of M dwarf stars, later extended and found to hold for all active late–type stars in both single and binary systems (Güdel & Benz 1993). They find that the soft X–ray and microwave luminosity of active late–type stars follows the relationship $\log L_x \approx \log L_R + 15.5$ quite precisely, where L_x is the soft X–ray luminosity and L_R the radio luminosity at 6 cm (and usually also at 3.6 cm, as these stars tend to have quite flat radio spectra). This relationship predicts a quiescent flux density of $\sim$0.07 mJy for each companion of the L726–8 system (dividing the soft X–ray flux equally between the two companions), more than an order of magnitude below that observed for UV Ceti. By comparison, the remaining active late–type stars considered by Güdel & Benz (1993) deviate from this relationship by a factor of only 2–3. For Proxima Centauri the above relationship predicts a quiescent stellar flux density of ∼0.2 mJy, a factor of 2 higher than our observed upper limit and therefore still compatible with our result within the observed spread. So far, apart from UV Ceti, the only other star known to be in clear conflict with the proposed correlation is the dM4e flare star Rositter 137B (interestingly, its proper motion K1 dwarf companion AB Dor satisfies this relationship). Rst 137B, at a distance of ∼15 pc (Guirado et al. 1995) and inferred age of 50 million yrs, displays a quiescent radio luminosity ∼30 times higher than that of UV Ceti, and violates the proposed correlation by being overluminous in radio by nearly 2 orders of magnitude. Pre–main–sequence stars with ages of order 1 million yrs also tend to be radio–bright with respect to the radio–soft X–ray relationship (Güdel & Benz 1993).

The upper limits placed on the radio luminosity of Proxima Centauri at 6 and 3.5 cm of $\sim 2 \times 10^{11}$ erg Hz^{-1} s^{-1} (or $\log L_{6/3.5cm} \approx 11.3$) are the most sensitive radio luminosity determinations achieved for a star other than the Sun. For comparison, the quiet Sun has $\log L_{3.5cm} \approx 10.8$, the active (non–flaring) Sun has $\log L_{3.5cm} \approx 11.15$, and during the strongest flares the Sun can attain $\log L_{3.5cm} \approx 12.4$ (e.g., Kruger 1979). When making this comparison, however, one should keep in mind that the surface area of Proxima Centauri is nearly 50 times smaller than that of the Sun.

Observations of nearby dMe flare stars with the VLA have resulted in the detection of ∼40% of these stars at 20 cm and/or 6 cm, with a greater fraction likely to be detected given more observing time or greater sensitivity (White, Jackson, & Kundu 1989 and references therein). Yet, in about 30 hrs of observations at both 6 and 3.5 cm, no emission has been detected at these wavelengths from Proxima Centauri. By contrast, we detected a 20 cm flare from the star in just a total of 1.7 hrs observing time over a 12 hr period. Thus, like other dMe flare stars, Proxima Centauri may be vigorous producer of coherent radio emission (at 20 cm). Unlike a large fraction of other dMe flare stars, however, Proxima Centauri appears to be a relatively weak (if any) producer of nonthermal gyrosynchrotron emission (at 6 and 3.5 cm).

5.2. Comparison with Photospheric Magnetic Field Parameters

There are, at present, no direct measurements (e.g., using the Zeeman effect) of the photospheric magnetic field strength and its filling factor on Proxima Centauri. Our detection of a 20 cm flare suggests the presence of quite strong magnetic fields in the corona of Proxima Centauri; using the usual argument that the flare is produced by electron–cyclotron maser emission at the second harmonic of the gyrofrequency, one infers a coronal magnetic field strength of ∼250 G. The very detection of starspots on Proxima Centauri by Benedict et al.

(1993) implies a non–negligible filling factor of strong photospheric magnetic fields. In lieu of direct measurements, however, we shall use several indirect arguments to infer the possible stellar photospheric magnetic field parameters, and compare them with the constraints we infer for the coronal magnetic field. First, we shall briefly summarize the presently popular view of stellar magnetic activity indicators, and of stellar magnetic field parameters, as they apply to late–type dwarf stars.

Vilhu & Walter (1987) showed that there exists a well defined upper limit in the chromospheric (as measured by the Mg II h and k resonance lines), transition region (C IV λ1550), and coronal (soft X–ray) emission of late–type dwarf stars. This upper limit is delineated by rapidly rotating stars with periods $P_{rot} \leq 5$ days, where as a ratio of their bolometric luminosity their chromospheric, transition region, and coronal output appear to be (approximately) constant over the spectral class range G0–M6. This has led to the idea that the entire disk of rapidly rotating stars is covered by magnetic structures responsible for both heating and confining the observed hot atmospheric plasma. The surface coverage of such active regions is presumed to be smaller on slower rotating and less active stars, thereby resulting in a decrease in the observed magnetic–activity related atmospheric emission.

The above picture seems to be consistent with Zeeman photospheric magnetic field measurements. These measurements indicate that kilogauss magnetic fields cover a large fraction of the photosphere of moderately rapidly–rotating ($P_{rot} \approx$ 5–10 days) G–K dwarfs, and that such fields essentially saturate the photosphere of rapidly–rotating ($P_{rot} \leq 4$ days) dMe flare stars (Saar 1990a and references therein). From these measurements, Saar (1987) and Linsky & Saar (1987) suggest that the field strength of photospheric magnetic flux tubes on active late–type dwarf stars is determined solely by the photospheric gas pressure, with the flux tubes maintaining equipartition with the photospheric gas energy density. In going to later spectral types, the photospheric gas pressure, and hence the field strength of photospheric magnetic flux tubes, increases because of the increase in stellar surface gravity (which more than offsets the decrease in photospheric gas temperature). For stars with rotation periods greater than ~4 days, Saar (1987) found that their average photospheric magnetic flux density, $< fB >$, decreases according to the relationship

$$< fB > \propto \ \Omega^{1.3} \ , \tag{3}$$

where Ω is the stellar angular velocity (i.e., inverse of the rotation period) (Saar 1990a and references therein). Because, of course, the magnetic field strength B maintains equipartition with the photospheric gas pressure independent of stellar angular velocity, this decrease in magnetic flux density $< fB >$ is thought to be caused by a decrease in the filling factor f.

In summary then, the observed saturation in magnetic–activity related atmospheric emission and strong photospheric magnetic fields both support the idea that essentially the entire surface of rapidly rotating late–type dwarf stars (with $P_{rot} \leq 4-5$ days) is covered by kilogauss magnetic fields confining hot plasma. As one progresses towards slower rotating stars, the filling factor of such active regions decreases. In this picture, the Sun is a prototypical example of a slowly rotating star with a small filling factor of active regions.

We shall now use several indirect arguments to investigate the likely filling factor of strong magnetic fields on Proxima Centauri, and, for comparison, UV Ceti. First, we use the ratio of its soft X–ray to bolometric luminosity, $L_x/L_{bol} \approx 2.4 \times 10^{-4}$ (e.g., Agrawal, Rao, & Sreekantan 1986; Fleming et al. 1993). This is significantly lower than the saturation limit of $L_x/L_{bol} \approx 10^{-3}$ observed for active late–type dwarf stars spanning the spectral class range G–M (e.g., Vilhu & Walter 1987); by comparison, during solar maximum the Sun has $L_x/L_{bol} \approx 10^{-5}$, an order of magnitude lower than on Proxima Centauri. Fleming et al. (1993) have shown that this saturation limit extends to stars as late as M6, although at present this statement rests on only one star, WX UMa. The other 4 stars with spectral class in the range M6–M7, and which were detected in soft X–rays, had ratios of L_x/L_{bol} of only a few times 10^{-4}, comparable to that of Proxima Centauri. If we assume that the average surface X–ray flux per unit area in active regions is the same for all stars of the same spectral class (independent of rotation period), one infers from L_x/L_{bol} (a factor of $\sim$4 below the saturation limit) that $\sim$25% of the surface of Proxima Centauri could be covered by X–ray loops with kilogauss fields; under the same assumption, one would infer that $\sim$1% of the surface of the Sun is covered by kilogauss fields during solar maximum, as is indeed observed. For a filling factor of $\sim$25%, less than half of the coronal loops on Proxima Centauri can be filled with the hot X–ray component, although the remaining loops could contain plasma at temperatures similar to the solar active region corona. The same analysis applied to UV Ceti would suggest that $\sim$25–50% of its disk can be covered by kilogauss X–ray loops, which would not be sufficient to explain the high-frequency microwave flux as gyroresonance emission. If on Proxima Centauri the photospheric field was to expand in the corona to cover the entire stellar disk (in which case, for a equipartition photospheric magnetic field strength of 5 kG, the average field strength in the low corona would still exceed 1 kG), then our observations imply that not all the loops can be filled with plasma at temperatures comparable to or higher than the solar active region corona; a fraction of the loops must contain significantly cooler plasma.

A second method for estimating filling factors is suggested by Saar & Schrijver (1987) (see also Saar 1988), who found an almost linear dependence between the mean surface soft X–ray flux, F_x, and the average photospheric magnetic flux density, $< fB >$, for active late–type dwarf stars of

$$F_x \approx 6 \times 10^3 < fB >^{0.90 \pm 0.10} \quad , \tag{4}$$

independent of spectral class from G–M. This, they suggest, may be evidence for a causal link between the surface soft X–ray flux and the photospheric magnetic flux density of these stars, as the same dependence appears to be seen on the Sun (according to Schrijver 1987). If we apply the above relationship to Proxima Centauri, then we expect $< fB > \approx 330$ G. For an equipartition field strength of $B \approx 5$ kG, $f \approx 7\%$. This is compatible with the upper limits to the filling factor of kilogauss X–ray coronal loops on Proxima Centauri implied by the radio data. We note, however, that using the same relationship, UV Ceti also would have a filling factor of kilogauss photospheric magnetic fields of only ∼7–14%, which again is inadequate to explain its high–frequency microwave flux as gyroresonance emission. One could postulate that on UV Ceti the photospheric field expands extremely rapidly with height to fill the entire low corona, and that all these field lines contain $\geq 10^7$ K plasma, thereby producing the proposed gyroresonance emission. Such a situation with $f_{photosphere} \ll 1$ but $f_{corona} \approx 1$ would make the behaviour of strong magnetic fields on UV Ceti quite different to the case on the Sun, and apparently also (many) other dMe flare stars (e.g., Proxima Centauri).

We wish to point out that Equation 4 was derived based on data for only a dozen stars and the Sun, although stars with rotation periods both shorter and longer than 5 days were included. The following argument, however, suggests that it may not be appropriate for late–type dwarf stars at the saturation limit. According to Saar (1987), for these stars the magnetic flux density ($< fB >$) increases towards later spectral types because of the increase in equipartition photospheric magnetic field strength (the filling factor stays approximately constant at or near unity). On the other hand, the measured surface X–ray flux (F_x) decreases towards stars of later spectral types; i.e., L_x/L_{bol} remains the same, but L_{bol} decreases much more rapidly than the stellar surface area (e.g., in going from G0 to M0, L_{bol} decreases by a factor of ∼20, but the stellar surface area decreases by only a factor of ∼3); this is consistent with the idea that the corona of smaller stars have a smaller volume, presumably because of a smaller scale height. This decrease in F_x with increasing $< fB >$ for stars at the saturation limit is opposite to the relationship of Equation 4 suggested by Saar & Schrijver (1987).

A third method for estimating filling factors is based on the stellar rotation rate. Benedict et al. (1993) recently found periodic photometric variations on Proxima Centauri that they attribute to starspots. They infer a rotation period of ∼41 days for this star, in close agreement with that prediced by Doyle (1987) based on an empirical relationship between the Mg II h and k flux and the rotation period of F–M dwarfs. From the relationship between magnetic flux density and rotation period specified by Equation 3, one would then infer that the magnetic flux density of Proxima Centauri is ∼15 times less than that of stars with similar spectral type but at the saturation limit; our radio results are compatible with this idea. The rotation period of UV Ceti has not been measured, but the empirical relationship of Doyle (1987) predicts a rotation period of ∼27 days for this star. According to Equation 4, UV Ceti should have a magnetic flux density ∼10 times less than that of stars with similar spectral type at the saturation limit, that is, a filling factor an order of magnitude less than complete saturation.

In summary, several lines of argument suggest that the filling factor of kilogauss photospheric magnetic fields on Proxima Centauri should be of order 10%. Since we expect that the mean field strength of magnetic loops in the lower corona will be of order $< fB >$ (WLK94) and therefore below the values needed to make the loops optically thick at 6 and 3.6 cm, such a low filling factor is compatible with our null detection of Proxima Centauri as a quiescent radio source at cm wavelengths, as the expected gyroresonance radio emission from X–ray–emitting loops with such a small filling factor is below our sensitivity level. The same arguments applied to UV Ceti predict a filling factor of kilogauss photospheric magnetic fields only slightly larger. Thus, the unusually high quiescent radio luminosity of UV Ceti (here referring specifically to the component attributed by Güdel & Benz (1989) to gyroresonance emission) by comparison to Proxima Centauri and other flare stars cannot at present easily be explained by the (indirect) data on their magnetic fields.

5.3. Limits on a Stellar Wind

Doyle & Mathioudakis (1991) and Mullan et al. (1992) have reported tentative detections of a number of dMe flare stars at 1 mm and, in a few cases, also at 2 mm. Mullan et al. (1992) attribute this emission to mass loss from an ionized stellar wind, and infer a mass–loss rate of a few times 10^{-10} $M_{\odot}$ yr^{-1}. This result, if correct, would have important implications for stellar evolution, and also the evolution of any planets around M dwarf stars. For example, if they experience such a high mass–loss rate throughout (the majority of) their lifetimes, mid–M dwarfs would completely dissipate before they reach the main sequence! Proxima Centauri, if coeval with the α Centauri system (a subject of considerable debate; see Matthews & Gilmore 1993) and therefore at an age of ∼6 billion yrs (Flannery & Ayres 1978), must have either descended from a significantly more massive star, or experienced such a high mass–loss rate over only a small fraction of its lifetime.

The interpretation of Mullan et al. (1992) is not consistent with our microwave data for Prox Cen. Two lines of argument suggest this. Firstly, the low radio luminosity we place on Proxima Centauri implies that (at least for this star) the mass–loss rate from any stellar wind is much less than that inferred above. Using the same parameters as Mullan et al. (1992), we infer a mass–loss rate of $\leq 7 \times 10^{-12}$ $(v_W/300$ km s$^{-1})$ $M_{\odot}$ yr^{-1} for Proxima Centauri (see their Eq. 2, but modified to 3.5 cm by using the fact that free–free emission from a stellar wind should have a radio spectral index of +0.6), where v_W is the stellar wind velocity (assumed to be 300 km s^{-1} by Mullan et al. 1992). This upper limit is nearly two orders of magnitude lower than the mass–loss rate inferred by Mullan et al. (1992) for other dMe flare stars. For comparison, based on a rather simple (and necessarily accurate) model, Badalyan & Livshits (1992) predict that active late–type stars should have a mass–loss rate of $\geq 10^{-11}$ $M_\odot$ yr^{-1}.

Secondly, a stellar wind of the magnitude inferred by Mullan et al (1992) would be optically thick to microwave emission at a height of at least $\geq 50 R_*$ above the stellar surface. However, the observed highly–polarized narrowband 20 cm flare requires either a relatively strong magnetic field of order 200 G if it is cyclotron maser emission, which is unlikely to be found at such radii, or else an electron density of order 2 $\times 10^{10}$ cm^{-3} if it is plasma emission; at such a density radio emission could never escape from a stellar wind as cool as 10^4 K because of strong free–free absorption.

6. CONCLUSIONS

The results of radio observations of Proxima Centauri at 20, 13, 6, and 3.5 cm suggest that, like other dMe flare stars, Proxima Centauri may be a prolific producer of coherent radio bursts at 20 cm. Unlike a large fraction of other dMe flare stars, however, it appears to be a weak (if any) producer of nonthermal gyrosynchrotron emission at 6 and 3.5 cm. At these wavelengths, the upper limit placed on its radio luminosity of $\sim 2 \times 10^{11}$ erg Hz^{-1} s^{-1} is the most sensitive determination for any star other than the Sun.

Our radio results, when considered together with existing soft X–ray data, place important constraints on the filling factor of ∼500—1000 G X–ray–emitting magnetic loops on Proxima Centauri. Loops at temperatures of $\sim 2 \times 10^7$ K, representative of the hot stellar X–ray component, have a projected area of less than ∼10% of the area of the stellar disk. Loops at temperatures of $\sim 3 \times 10^6$ K, representative of the cool stellar X–ray component (but similar in temperature to the non–flaring solar active region corona), have a filling factor less than ∼90%. Our results are compatible with present empirical relationships that predict, based on the measured stellar rotation period of $P_{rot} \approx 41$ days and the ratio of its soft X–ray to bolometric luminosity of $L_x/L_{bol} \approx 2.4 \times 10^{-4}$, that the filling factor of kilogauss photospheric magnetic fields and kilogauss X–ray loops on this star should be of order 10–20%. Such a photospheric field distribution will lead to mean magnetic field strengths in the lower corona of Prox Cen which are too weak to support optically thick thermal gyroresonance microwave emission over a large enough area to have been detected. These empirical relationships predict that UV Ceti should have approximately the same magnetic parameters as Proxima Centauri. Yet, compared to Proxima Centauri, UV Ceti displays quiescent radio emission that is more than an order of magnitude more luminous.

Finally, the upper limit placed on the radio luminosity of Proxima Centauri implies that any stellar wind has a mass–loss rate of $\leq 7 \times 10^{-12}$ $(v_W/300\ \mathrm{km\ s^{-1}})$ $M_\odot$ $\mathrm{yr^{-1}}$. The latter is almost 2 orders of magnitude lower than that inferred by Mullan et al. (1992) from mm wavelength observations of other dMe flare stars. Such a high mass–loss rate is untenable if our present understanding of the cm wavelength radio emission of dMe flare stars is correct.

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Figure Legends

Figure 1

Temporal morphology of the flare at 20 cm from Proxima Centauri in (a) Stokes I, and (b) Stokes V. Each point corresponds to a 60 s integration, and has an error bar of length $\pm 1\sigma$.

Figure 2

Undeconvolved radio images of the flare shown in Figure 1 in (a) Stokes I (contour levels are 7.0, 9.5, and 12.0 mJy), and (b) Stokes V (contour levels are -5.0, -9.0, and -10.8 mJy). Background sources have been subtracted from the Stokes I image; no background sources were apparent in the Stokes V image. The flaring source appears as a stripe because the instantaneous response of the ATCA is a stripe (accompanied by weaker parallel stripes corresponding to sidelobes) orthogonal to the long axis of the linear array. The cross indicates the extrapolated optical position of Proxima Centauri during the observation (see text), and has arms of length $5''$.

Figure 3

Radio image at 3.5 cm of the region surrounding Proxima Centauri. Contours are at intervals of -3σ, -2σ, -1σ, 1σ, 2σ, 3σ, 5σ, and 10σ, where $1\sigma = 120$ μJy The optical position of the star is indicated by a cross, which has arms of length $5''$.

TABLE 1. Radio Observations of Proxima Centauri

Date	Time	Wavelength	Flux Density
1990 Jul 24	01:00–14:21	6 cm	$< 250\mu$Jy
1991 Aug 31	00:55–13:40	20 cm	$< 310\mu$Jy[a]
	00:40–13:30	13 cm	$< 420\mu$Jy
	00:33–13:18	6 cm	$< 470\mu$Jy
	00:22–13:07	3.5 cm	$< 550\mu$Jy
1993 Sep 16	07:14–12:27	6 cm	$< 200\mu$Jy
		3.5 cm	$< 230\mu$Jy
1994 May 25	05:24–20:45	6 cm	$< 110\mu$Jy
		3.5 cm	$< 120\mu$Jy

[a]One flare detected

TABLE 2. Optical Position and Proper Motion of Proxima Centauri

Source	α	δ	pm_α	pm_δ
Simbad database	14:29:43.41	-62:40:44.4	$-3''.730 \pm 0''.009$	$0''.772 \pm 0''.020$
Hipparchos input catalog	14:29:42.91	-62:40:47.2	$-3''.740\pm?$	$0''.756\pm?$
Benedict et al. (1993)	14:29:43.00	-62:40:46.1		

Positions are for equinox 2000, in J2000 coordinates

TABLE 3. Summary of published soft X–ray observations of Proxima Centauri

Date	Observatory	L_x (erg Hz^{-1} s^{-1})	references
1979 Mar 6–7	*EINSTEIN*	$\sim 1.5 \times 10^{27}$	1, 2
1980 Aug 20	*EINSTEIN*	$\sim 5 \times 10^{26}$	3
1985 Mar 2–3	*EXOSAT*	$\sim 1.5 \times 10^{27}$	4,5
1990 Aug 7–10	*ROSAT*	$\sim 1.4 \times 10^{27}$	6

References for Table 3.

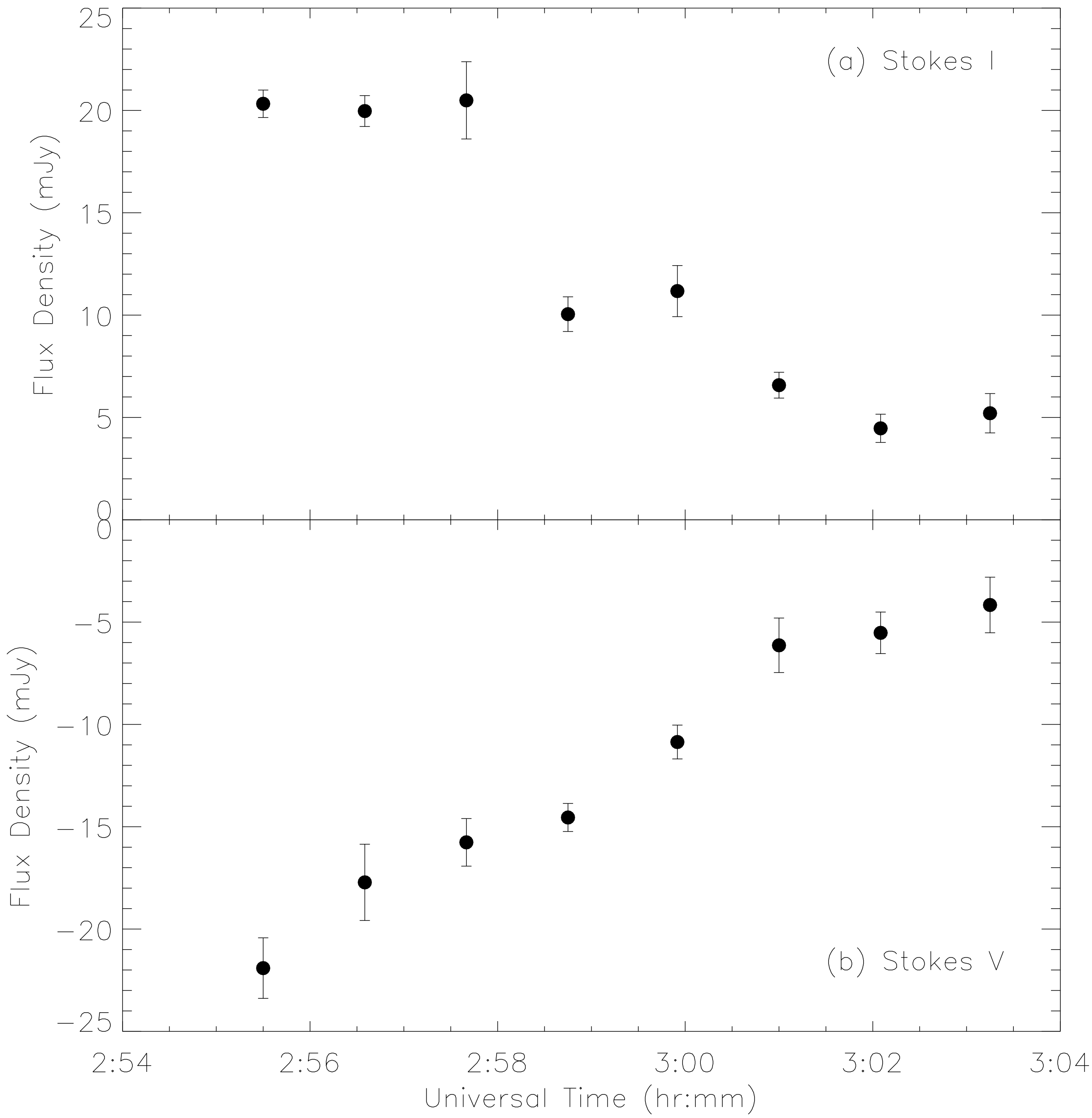
(1) Haisch & Linsky (1980); (2) Haisch et al. 1980; (3) Haisch et al. 1983; (4) Collura, Pasquini, & Schmitt 1988; (5) Pallavicini, Tagliaferri, & Stella 1990; (6) Fleming et al. 1993

Notes to Table 3.

One flare also was detected in the 1979 Mar 6–7, 1980 Aug 20, and 1985 Mar 2–3 observations, while several were detected in the 1990 Aug 7–10 observations. The latter period corresponds to the *ROSAT* all–sky survey.

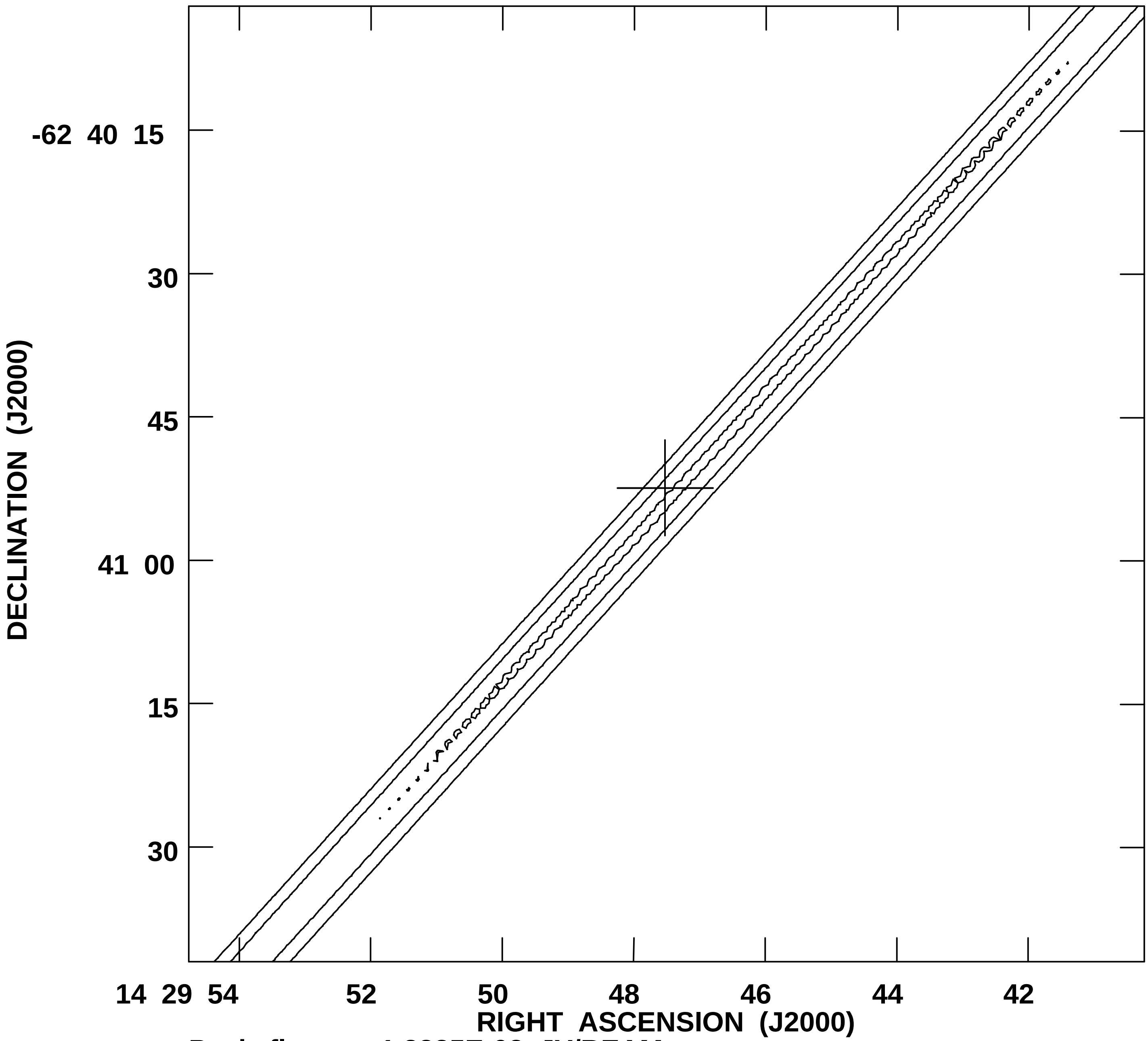
TABLE 4. Constraints on properties of coronal magnetic loops on Proxima Centauri

Radio wavelength	Radio flux	Soft X–ray temperature	Magnetic field strength	Filling factor
6 cm	110 μJy	$\sim 3 \times 10^6$ K	≥ 430 G	2.36
		$\sim 2 \times 10^7$ K	≥ 430 G	0.35
3.5 cm	120 μJy	$\sim 3 \times 10^6$ K	≥ 610 G	0.88
		$\sim 2 \times 10^7$ K	≥ 610 G	0.13



(a) Stokes I
(b) Stokes V
Flux Density (mJy)
Flux Density (mJy)
Universal Time (hr:mm)
25
20
15
10
5
0
0
−5
−10
−15
−20
−25
2:54
2:56
2:58
3:00
3:02
3:04

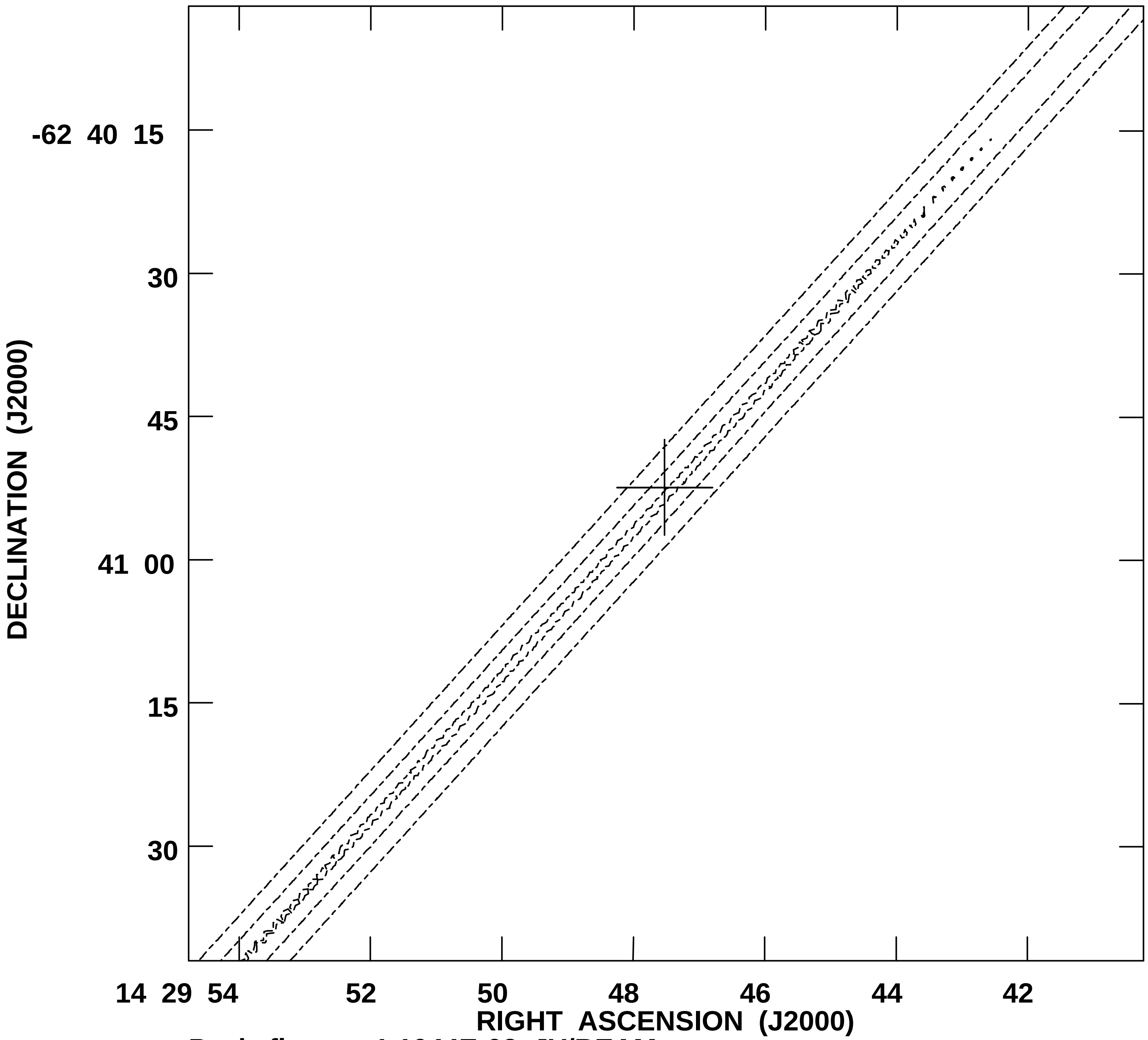
PLot file version 14 created 09-MAY-1995 16:46:03
proxcen IPOL 1468.000 MHZ PROX_CEN_L.IMAP.1



Peak flux = 1.2325E-02 JY/BEAM
Levs = 1.0000E-03 * (7.000, 10.00, 12.00)

PLot file version 12 created 09-MAY-1995 16:49:56

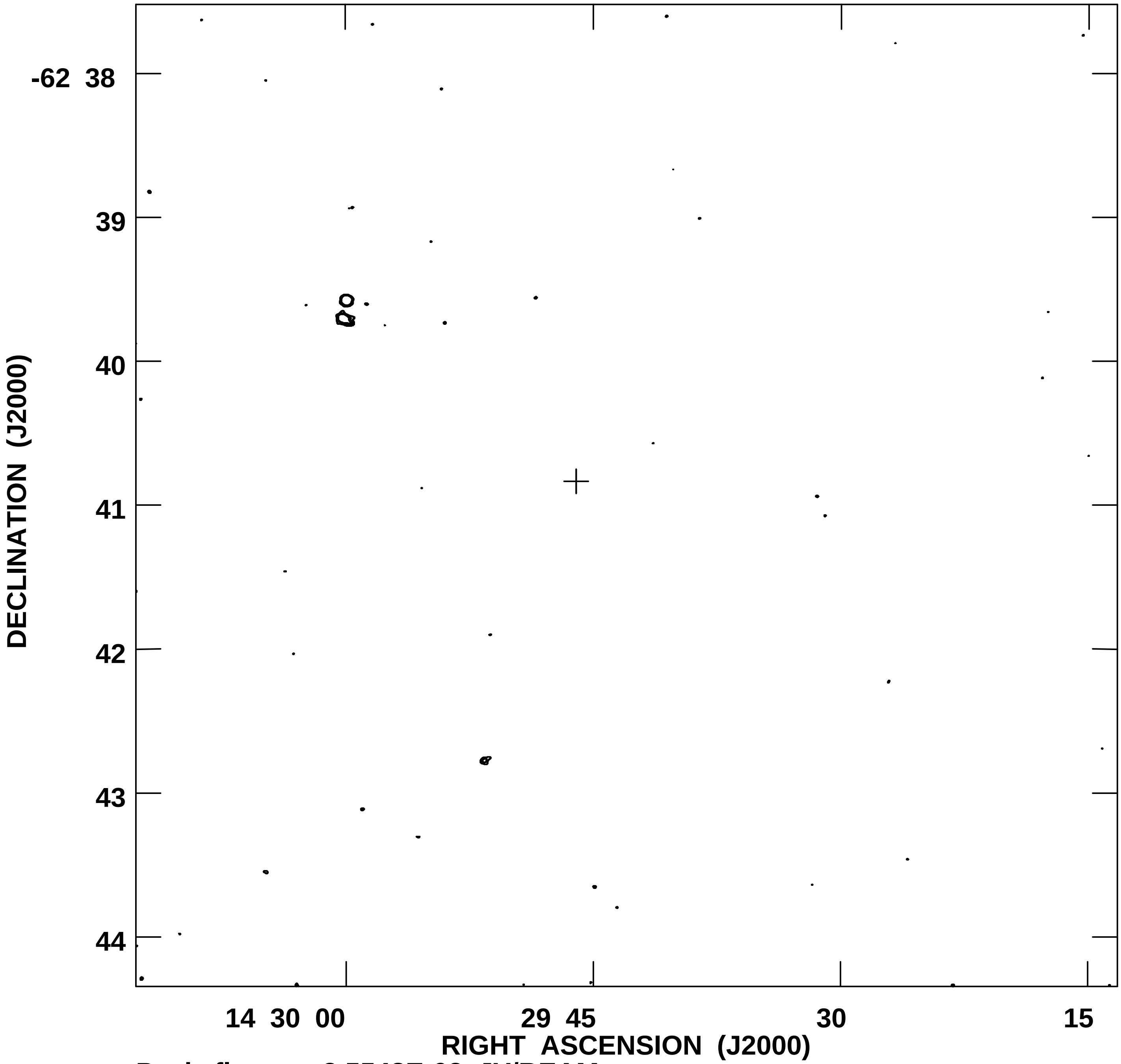
proxcen VPOL 1468.000 MHZ PROX_CEN_L.VMAP.1



Peak flux = -1.1044E-02 JY/BEAM

Levs = -1.0000E-03 * (5.000, 9.000, 10.80)

PLot file version 7 created 10-MAY-1995 09:18:08
prox cen IPOL 8640.000 MHZ PROXCEN.ICLN.1



Peak flux = 3.5548E-03 JY/BEAM
Levs = 1.2000E-04 * (-3.00, -2.00, -1.00,
1.000, 2.000, 3.000)