

Non-thermal radio emission from post-main-sequence stars

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SUMMARY

The Australia Telescope Compact Array (ATCA) has been used to make 4.8-GHz observations of 24 fields containing post-main-sequence stars. These stars were selected from a sample of late-type (spectral types G, K and M) giants and bright giants within 30 pc claimed by Slee *et al.*, from observations with the Parkes radio telescope, to be variable non-thermal radio emitters. No significant 4.8-GHz radio emission was detected from these stars. Non-detection of any stars with the ATCA is an improbable result (given the claimed Parkes detection rates and the superior sensitivity of the ATCA), and calls for a re-analysis of the original Parkes 8.4-GHz observations. Our re-analysis suggests that the majority of the claimed Parkes detections with $S \leq 8$ mJy are false. The five claimed Parkes detections with $S > 8$ mJy are discussed individually on the basis of the ATCA and Molonglo Observatory Synthesis Telescope (MOST) observations.

The claimed Parkes detection of non-thermal radio emission from some members of this sample would contradict our current understanding of magnetic field generation and atmospheric structure in late-type stars. We conclude that the Parkes, ATCA and MOST observations do not invalidate the concept of a 'coronal boundary line' between stars exhibiting chromospheric and coronal emission, and more evolved stars displaying only cool winds.

1 INTRODUCTION

Observations of stellar activity indicators such as Ca H and K line-core reversals and non-thermal radio emission provide information about emission processes, physical conditions and (indirectly) levels of magnetic field generation in late-type main-sequence (MS) and post-main-sequence (PTMS) stars. If we accept the solar analogy of photosphere–chromosphere–transition region–corona as representative of the outer atmospheric structure of late-type stars, X-ray and non-thermal radio emission reflect physical processes occurring in the corona. Our current understanding of how radio emission is generated in the coronae of late-type stars has been reviewed by Dulk (1985) and Kuipers (1985); microwave emission is usually attributed to gyrosynchrotron, synchrotron or cyclotron maser processes, involving the acceleration of non-thermal distributions of electrons in the presence of coronal magnetic fields. The observed emission typically has a zero or positive spectral index (defined by $S \propto \nu^\alpha$) at lower frequencies which turns negative at microwave wavelengths.

The internal and atmospheric structure of PTMS stars changes rapidly as they leave the MS and evolve towards and

up the red giant branch, and dramatic changes are seen in most activity indicators. X-ray and UV observations have identified abrupt discontinuities in emissions levels, the 'Linsky–Haisch dividing line' (Linsky & Haisch 1979) and a 'coronal boundary line' (Ayres *et al.* 1981; Vaiana *et al.* 1981; Maggio *et al.* 1990). Stars hotter than these 'dividing lines' show emission lines from 1×10^5 K gas and significant X-ray fluxes, indicating the existence of transition regions and coronae, while cooler stars display chromospheric ($< 2 \times 10^4$ K) gas and P-Cygni line profiles, implying stellar winds and mass loss. The existence of a small but clearly defined group of 'hybrid' stars (Hartmann, Dupree & Raymond 1981) displaying both high-temperature transition-region lines and cool winds should also be noted as it indicates that some intermediate cases exist. These abrupt changes in emission levels presumably reflect evolutionary changes in the internal and outer atmospheric structure of PTMS stars.

The absence of detectable coronae in single PTMS stars evolving through the region would suggest a decline in non-thermal radio emission, and the results of previous surveys of these stars (e.g. Fix & Spangler 1976; Drake & Linsky 1986) appear consistent with this picture. However, a recent 8.4-

GHz survey of all late-type giants and bright giants within 30 pc and south of the celestial equator, using the Parkes radio telescope, claimed to detect 24 stars out of a total sample of 82, at a typical level of 4 mJy (Slee *et al.* 1989, hereafter SS89). Over a third of the claimed detections were on the cool side of the coronal boundary line, and indicated the existence of coronae in some stars as late as M3. Previous surveys have not detected non-thermal emission from such stars, e.g. a 1986 VLA survey by Drake & Linsky (1986), who observed 39 single cool giants and detected only weak (< 1 mJy) emission from five stars which they attributed to thermal emission from cool stellar winds, although there are unconfirmed reports of single-dish detections of radio flares from red giants (e.g. Boice *et al.* 1981).

To test the Parkes result, we have made 4.8-GHz observations with the ATCA of 24 fields containing all stars claimed to have been detected by SS89. These data have been used in conjunction with 843-MHz observations made by the Molonglo Observatory Synthesis Telescope to search for stellar radio emission and/or any nearby confusing sources. Section 2 examines the results of the ATCA and MOST observations. Section 3 is a re-analysis of the Parkes 8.4-GHz observations. In Section 4, the five claimed 8.4-GHz sources detected at > 8 mJy are discussed individually, using the ATCA and MOST data, and in Section 5 we discuss the implications of our results on the present understanding of radio emission in late-type PTMS stars.

2 OBSERVATIONS

2.1 ATCA

The ATCA is an earth-rotation synthesis telescope comprised of five 22-m dishes on a 3-km track situated near Narrabri, NSW. Manchester (1991) has described the telescope and its capabilities. The observations were made in six sessions (1990 April 30, June 7, October 27, and 1991 January 5 and 13, May 4) at an operating frequency of 4.8 GHz. An observation for any one star usually involved three or four 30-min integrations (or ‘cuts’) at different hour angles; in some cases the cuts for a particular star were done in different observing sessions. The sources PKS 1934 – 638 (6.33 Jy) and PKS 1057 – 797 (2.3 Jy) were used as flux density calibrators. The typical synthesized beam FWHP for our data was ~ 4.5 arcsec. The 4σ sensitivity limit for these observations was typically ~ 0.8 – 1.2 mJy, where σ is the measured rms value of adjacent blank areas in each field. The data were reduced using the AIPS package running on a C-220 Convex.

In Table 1 we list the results of ATCA observations of the 24 stars claimed to have been detected by SS89. The stellar data have been taken from the Bright Star Catalogue (Hoffleit & Jaschek 1982). In columns 7 and 8 we have listed the SS89 claimed detection rates and peak emission levels; each observation refers to the mean of 10 wags (further discussion of the Parkes data can be found in the next section). In column 9 we list the 4σ upper limits for the 4.8-GHz flux density of the stars from the ATCA observations. Our criterion for detection was a 4σ source within 5 arcsec of the optical position. *In no case was there an unambiguous detection of stellar emission.* On the assumption that the spectrum is flat between 4.8 GHz and 8.4 GHz, and that the radio emission from these stars varies on time-scales of a day, the

probability of observing all 24 fields without detecting any stellar emission is < 0.001 (based on the Parkes detection rates, and assuming all the ATCA observations of any field were done on a single day). In four cases (HD 6805, HD 94510, HD 121474 and HD 203387) enough cuts were done on individual days to allow comparisons of the field between observing runs; no source is seen at the stellar position on any day.

2.2 MOST

Column 10 indicates whether Molonglo observations of that field were available. The MOST is an 843-MHz earth-rotation synthesis telescope (Mills 1981) operated by the University of Sydney. A 12-hr synthesis yields a beamwidth of 42 arcsec and a sensitivity limit of ~ 1 mJy beam $^{-1}$. Syntheses were made between 1987 October and 1989 February of six of the 24 fields, and two fields were coincidentally observed as a part of the Molonglo Survey of the Galactic plane (Whiteoak 1991). In no case was a source > 1 mJy detected at the stellar position. A few background sources were identified in both the MOST and ATCA images, with typical spectral indices of ~ -0.6 to -1 . Previous observations of active stars (Beasley, Large & Vaughan 1987; Large *et al.* 1989) indicate that the MOST usually only detects flaring stellar emission, and at a level typically an order of magnitude below detected 8.4-GHz fluxes. The lack of Molonglo detections is therefore not surprising, given the low detection rate and flux densities claimed for the Parkes sample.

3 RE-ANALYSIS OF PARKES 8.4-GHZ DETECTIONS

The absence of 4.8-GHz detections, coupled with the low probability of observing the complete sample without detecting any of the stars, led us to re-examine the SS89 result. The Parkes red giant survey published by SS89 involved six observing sessions from 1987 February to 1988 July. The observing method was identical to that used by Slee *et al.* (1987) in their microwave survey of southern active stars. Briefly, the telescope is pointed at the source for a 10-s integration, then driven in azimuth (‘wagged’) 2.5 beamwidths off source. At this reference position, an integration determines a background level for the observations to be subtracted from the on-source measurement. The mean and standard error for each set of 10 wags is recorded, corresponding to one observation. The standard error of the mean of a set of 10 wags was typically ~ 1.5 – 1.6 mJy; this variation is usually attributed to instrumental and atmospheric effects. The criterion for detection in SS89 was a positive flux density value $> 3\sigma$ for the mean of 10 wags (where σ was the measured standard error of that particular observation). To establish the validity of using Gaussian statistics to assess the significance of their observations, the distribution of 10-wag means between -4.0 and $+4.0$ mJy (several hundred sets of wags) was claimed by SS89 to be fitted by a Gaussian with zero mean and a standard deviation of 1.6 mJy. This result implied a 3σ sensitivity limit of ~ 4.8 mJy.

Fig. 1 shows a histogram of the SS89 observations (derived from the original data kindly supplied by O. B. Slee) between ± 20 mJy. The clear bars indicate the

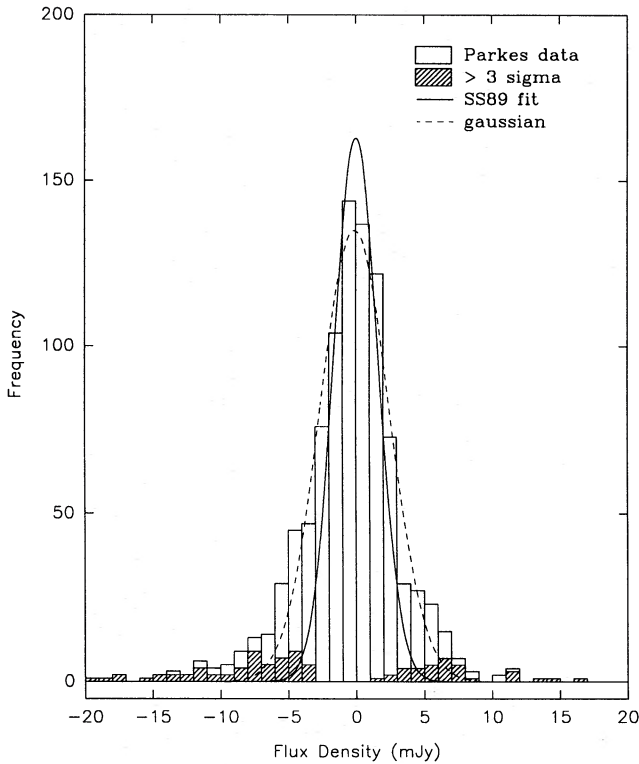


Figure 1. Parkes 8.4-GHz flux density frequency distribution. The shading indicates the proportion of claimed detections (i.e. $> 3\sigma$). The solid line is the SS89 Gaussian fit. The dashed line is the Gaussian fit derived in this paper with a standard deviation of 2.5 mJy.

frequency distribution of observed flux densities, the shaded area denoting the proportion of $> 3\sigma$ measurements (this has been done for both positive and negative flux density measurements). The solid line is the SS89 Gaussian fit to the distribution of flux densities between ± 4 mJy used to assess the sensitivity limit for the sample. It is clear from Fig. 1 that restricting the fit to ± 4 mJy has severely underestimated the width of the distribution; many measurements of low significance have been made above the 4.8-mJy limit suggested in SS89.

The wagging method, used by SS89, of subtracting a reference level measured 2.5 beamwidths away allows the non-detections to be examined as a survey of blank positions in the sky 2.5 beamwidths away from known stars. The reference-level subtraction means that if a real source exists in the reference beam, a net negative flux will be recorded. Therefore, the distribution of negative fluxes (which is determined identically by the telescope, atmospheric effects and confusion) can be used to assess the response of the telescope to (by hypothesis) a blank piece of sky. The distribution of negative flux densities in Fig. 1 is similar to the positive distribution for flux densities < 10 mJy for both claimed detections ($> 3\sigma$) and non-detections. Importantly, there is a long tail in the distribution of non-detections for negative and positive flux densities in the region where the bulk of the Parkes detections have been claimed (3–8 mJy). In summary, the distribution of measured positive flux densities below 8–10 mJy appears similar to the distribution

measured when there is (by hypothesis) no source in the beam.

Fig. 1 also shows a Gaussian fit to the frequency distribution of all measured Parkes flux densities. The fitted Gaussian has a standard deviation of 2.5 mJy, implying a 3σ sensitivity limit of 7.5 mJy. Based on this fit and the above arguments, we conclude that little significance should be attached to single 10-wag means less than approximately 8 mJy, regardless of the measured standard error. Most of the low flux-density Parkes detections (< 8 mJy) are therefore measurements of a normal distribution of errors derived from such effects as systematic offsets in the instrument, atmospheric variations or, in some cases, weak confusion (e.g. stars close to the Galactic plane). It should be emphasized that this does not mean these stars are not weak radio emitters, but that it is not possible to make unambiguous detections at these low flux densities based on the SS89 data, i.e. single-dish observations close to the instrumental sensitivity limit. This conclusion is consistent with the absence of 4.8-GHz detections using the ATCA (Table 1).

Table 1. ATCA survey results.

HR	HD	Other	V	Sp	d(pc)	SS89 Det.	SS89 mJy	ATCA mJy	MOST
			mag						
334	6805	η Cet	3.45	K1.5III	24.4	2/15	2.9	< 1.1	
402	8512	θ Cet	3.60	K0IIIb	24.4	1/16	6.7	< 1.0	
1008	20794		4.27	G8III	6.2	2/15	4.2	< 0.8	
1175	23817	β Ret	3.85	K1-2III	20.0	2/15	5.4	< 1.4	x
3085	64572		5.43	K0III	28.6	1/12	2.5	< 1.1	
3347	71878	β Vol	3.77	K1III	23.8	2/10	4.4	< 0.9	x
3477	74772		4.07	G5III	19.6	8/10	23.7	< 0.9	x
4257	94510		3.78	K1III	16.9	5/11	68.0	< 0.6	x
4671	106849	ϵ Mus	4.11	M5III	21.7	2/10	5.3	< 1.3	
5068	116976	69 Vir	4.76	K1IIIV	16.9	1/9	7.2	< 0.9	
5241	121474		4.71	K0III	30.3	8/11	11.7	< 0.8	x
5381	125932	51 Hya	4.77	K4III	25.0	1/11	3.4	< 1.4	
5548	131430	12 Lib	5.30	K2III	24.4	4/11	4.4	< 0.9	
5838	139997	κ Lib	4.74	M0IIIb	25.0	2/14	6.8	< 1.7	
6196	150416		4.96	G7.5II	21.3	3/14	5.9	< 1.4	
6832	167618	η Sgr	3.11	M3.5III	22.2	2/11	3.4	< 0.8	x
6842	167818		4.65	K3II	30.3	6/10	8.1	< 1.2	
6913	169916	λ Sgr	2.81	K1IIIb	18.9	1/10	5.1	< 1.0	
7078	174116	29 Sgr	5.24	K4III	29.4	2/14	5.5	< 1.0	x
7149	175751	η Sct	4.83	K2III	25.6	2/9	3.4	< 1.5	
7317	180928		6.06	K3III	24.4	2/8	3.7	< 1.0	
7581	188114	ι Sgr	4.13	K0II-III	28.6	1/8	22.0	< 0.9	x
8039	199951	γ Mic	4.67	G6III	29.4	2/11	5.7	< 0.9	
8167	203387	ι Cap	4.28	G8III	30.3	3/11	7.3	< 0.8	

Notes. Stellar data from Hoffleit & Jaschek (1982); V is the visual magnitude, Sp the spectral type. Columns 7 and 8 are the claimed SS89 8.4-GHz detection rates and peak flux densities. The number on the left in column 7 represents the number of claimed SS89 detections, the number on the right the total number of 8.4-GHz observations; each observation refers to a 10-wag mean. ATCA flux density upper limits represent the 4σ level. Stars with a cross in column 10 were observed at the MOST.

4 INDIVIDUAL SOURCES

In this section, we examine individually the five claimed SS89 detections above the more conservative 8-mJy sensitivity limit.

HD 74772 (HR 3477)

The claimed peak 8.4-GHz flux density for this star is 23.7 ± 4.2 mJy, with six claimed flux densities greater than 8 mJy. The ATCA 4.8-GHz observation indicates no significant emission from the star. Molonglo observations of this field indicate a sharp ridge of emission and extended low-level structure from the nearby Vela supernova remnant at the stellar position (Fig. 2). Milne (1968) and Milne & Manchester (1986) have published 2.7-GHz maps of this region extending out to the stellar position, indicating significant emission from the supernova shell. If the spectral index is -0.3 (Milne & Manchester 1986), the extended emission component in this region will be ~ 700 mJy beam $^{-1}$ at 8.4 GHz. In principle, the wagging technique used at Parkes should be insensitive to broad extended structure (as it involves the subtraction of a nearby reference level), but small spatial gradients and inhomogeneities in the emission (demonstrated in the MOST map) could easily account for the observed 8.4-GHz Parkes flux densities. We therefore reject the claimed detection of HD 74772 on the grounds of confusion.

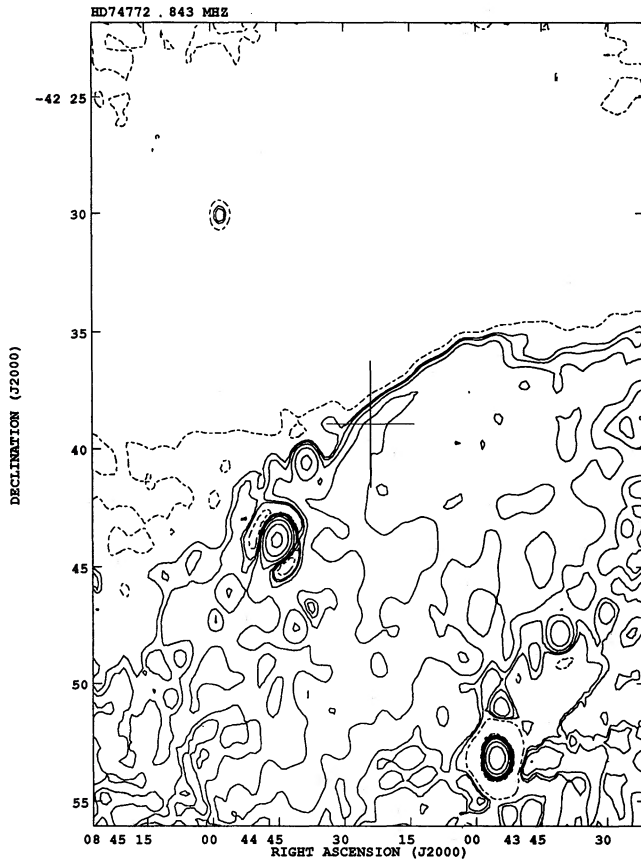


Figure 2. MOST 843-MHz image of the HD 74772 field. The cross denotes the stellar position. The extended emission in the southwest is part of the Vela SNR. The contour levels are -2 (dashed), 1, 2, 4, 8, 16, 32, 64, 128 mJy beam $^{-1}$.

HD 94510 (HR 4257)

The claimed peak 8.4-GHz flux density for this star is 68.0 ± 3.3 mJy, with four claimed flux densities greater than 8 mJy. The ATCA 4.8-GHz observation shows no source with $S > 1$ mJy within 8 arcmin of the stellar position; enough cuts of HD 94510 were taken during two of the observing sessions to allow separate syntheses, but no significant differences in the field were seen. This star is on the Galactic plane ($l = 288^\circ 18'$, $b = 0^\circ 6'$) and is only 2° away from the Carina nebula. The 843-MHz MOST image of this region shows extended emission associated with the nebula near the stellar position. Previous Parkes and Fleurs observations of the Carina nebulae at 5 GHz and 1.4 GHz (Gardner *et al.* 1970; Retallack 1983) detected strong emission extending well over a degree from the central homunculus. We reject the SS89 detection of HD 94510 because of three possible sources of confusion; the extended emission from the nebula itself, a varying sidelobe response on some region of the nebula, or the Galactic plane itself.

HD 121474 (HR 5241)

The claimed peak 8.4-GHz flux density for this K0III star is 11.7 ± 3.1 mJy. ATCA observations show no significant sources of emission within 2 arcmin of the stellar position. Separate syntheses of ATCA cuts from different observing runs give similar negative results. Molonglo observations of this field indicate a 722-mJy source approximately 22 arcmin away. This star is near the Galactic plane ($l = 310^\circ 2'$, $b = -1^\circ 75'$), which must place some doubt on the validity of the SS89 detection due to the possibility of weak extended sources and structure in the background emission in the main beam or sidelobes.

HD 167818 (HR 6842)

The claimed peak 8.4-GHz flux density for this K3II star is 8.1 ± 1.6 mJy. The ATCA observation of this field detected no significant (> 1 mJy) sources within 5 arcmin of the stellar position. The weak claimed SS89 flux density makes this a marginal detection, and further observations of this star should be made.

HD 188114 (HR 7581)

This K0II–III star has a claimed SS89 peak flux density of 22.0 ± 5.7 mJy. In Fig. 3, the ATCA observation of this field is shown. There is no source > 1 mJy (4σ) within 2 arcmin of the stellar position. The MOST observation of this field does show a weak (~ 6 mJy) source close to the stellar position which is possibly detected at ~ 0.8 mJy in the ATCA image (outside the displayed field) approximately 2 arcmin northwest of the stellar position. The large error for the claimed SS89 detection (a factor of four higher than typical values) casts some doubt on this detection.

5 DISCUSSION

The SS89 detections of non-thermal radio emission imply the existence of coronae and therefore dynamo-generated magnetic fields in stars as late as M3. The ATCA and MOST

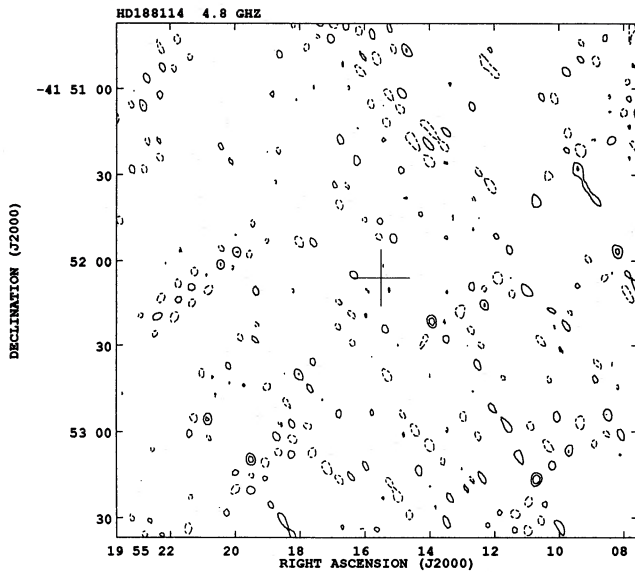


Figure 3. ATCA 4.8-GHz image of HD 188114. The cross denotes the stellar position. The contour levels are -0.46 (dashed), 0.46 , $0.69 \text{ mJy beam}^{-1}$ ($\pm 2\sigma$, 3σ , where σ is the rms of blank regions of the field).

observations, combined with a re-analysis of the SS89 observations, indicate that the majority of the claimed SS89 detections are likely to be incorrect; there remain only two marginal detections close to the sensitivity limit derived in this paper for the SS89 mode of observation. If we assume that these two detections are real, then both stars (HD 121474 and HD 167818) are of spectral type early K, which does not violate the coronal boundary line hypothesis. Significantly, the lack of 4.8-GHz ATCA detections supports the Drake & Linsky (1986) conclusion that late-type single giants show no significant non-thermal radio emission.

The detection of non-thermal radio emission from late-type PTMS stars would have profound implications for theories of how magnetic fields are generated in stars. In our current understanding of the origin of stellar activity, a dynamo process between rotation and convection in the stars generates the magnetic field of the star, which then floats (or is dragged) to the surface to form complex magnetic loop structures, similar to those seen on the Sun (see reviews by Parker 1970; Belvedere 1985; Beasley & Cram 1990). On the Sun, the bulk of the observed flaring and non-flaring X-ray emission and radio emission comes from magnetic structures such as active regions and coronal loops.

The evolutionary changes in structure for stars evolving off the MS directly affect these processes. On the MS, early-type stars have high rotation but no convection zones, and therefore are not expected to show evidence of magnetic activity (although VLA observations by Abbott 1985 have detected non-thermal emission from O- and B-type stars). As the stars evolve off the MS and approach the red giant branch, they develop deep convection zones, enabling the generation of magnetic fields, presumably through a dynamo process similar to that in MS stars. These stars are also experiencing an internal redistribution of angular momentum as their moment of inertia increases (Endal & Sofia 1979; Gilliland 1985; Rutten & Pylyser 1988), and possible rotational braking through the interaction of the stellar wind

with the dynamo-generated magnetic field (Gray 1989). The decrease in rotation rate as a star evolves through this region of the HR diagram (spectral types G0–K0) leads to a decline in the overall level of magnetic field generation, and a subsequent decline in activity indicators like Ca H and K and microwave radio emission (Rutten 1987; Rutten & Pylyser 1988; Beasley 1991). It should be stressed that this decline in emission levels is not the same as the Linsky–Haisch dividing line or the coronal boundary line; they are adjacent in the HR diagram, but clearly separate.

A class of stars which clearly demonstrate this important difference is the RSCVn stars (Hall 1976). These consist of a late-type giant or subgiant star in a close-binary system with an earlier MS or PTMS star. The late-type stars in RSCVn binaries are usually radio emitters, and extensive radio observations of this class of star have been made (Mutel & Lestrade 1985; Slee *et al.* 1989; Drake, Simon & Linsky 1989). It is believed that the enhanced rotation caused by tidal synchronization in the close-binary system leads to the enhanced levels of activity. The fact that these stars can be detected up to the coronal boundary line is important; presumably as these stars evolve through the coronal boundary line, their dynamos are still generating significant magnetic fields (as the stars have not spun down). This allows us to speculate that the coronal boundary line represents the effect of stellar evolution on atmospheric structure and the emission processes rather than on the dynamo process, e.g. the changing stellar gravity causing instabilities in hot ($T \sim 10^6 \text{ K}$) coronal structures, giving preference to less-luminous smaller and cooler loops (Antiochos & Noci 1986). The Linsky–Haisch dividing line and coronal boundary line may represent the effects of evolutionary changes in stellar structure on the dynamo process itself, e.g. an evolution from closed field lines and loop structures in the transition region and corona (allowing confinement and heating of the stellar material) to open field lines (similar to coronal holes) and cool winds.

The origin of the abrupt changes in the emission levels from these stars remains unclear. The difficulty lies in differentiating between the effects of stellar evolution on the dynamo process and the actual emission mechanisms, and reconciling our poor understanding of both these physical processes with a complicated observational picture.

6 CONCLUSIONS

ATCA and MOST observations of a sample of 24 stars claimed to be 8.4-GHz radio emitters have failed to detect stellar radio emission at 4.8 GHz and 843 MHz. A re-analysis of the original Parkes data indicates that the criterion used to determine the significance of those observations underestimated the sensitivity limit of the data, and we now believe that the majority of the SS89 8.4-GHz detections are false. Individual examination of the five stars claimed by SS89 as detected above a more conservative sensitivity limit of $\sim 8 \text{ mJy}$ (derived in this paper) indicates that two are clearly misidentifications due to confusion, one possibly the result of a poor observation, while the remaining two detections must be considered marginal.

We conclude that, based on ATCA, MOST and Parkes radio observations of late-type PTMS stars, there is no evidence to suggest any contradiction of the coronal

boundary hypothesis derived from UV and X-ray observations. This failure to detect significant radio emission from these stars at all three frequencies is consistent with previous observations and our current theories concerning the observed effects of stellar evolution on emission mechanisms and/or dynamo processes.

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REFERENCES

- Abbott, D. C., 1985. In: *Radio Stars*, eds Hjellming, R. M. & Gibson, D. M., Reidel, Dordrecht.
- Antiochos, S. & Noci, G., 1986. *Astrophys. J.*, **301**, 440.
- Ayres, T. R., Linsky, J. L., Vaiana, G. S., Golub, L. & Rosner, R., 1981. *Astrophys. J.*, **250**, 293.
- Beasley, A. J., 1991. *PhD Thesis*, University of Sydney, in preparation.
- Beasley, A. J. & Cram, L. E., 1990. *Solar Phys.*, **125**, 191.
- Beasley, A. J., Large, M. I. & Vaughan, A. E., 1987. *Proc. Astr. Soc. Aust.*, **7**, 46.
- Belvedere, G., 1985. *Solar Phys.*, **100**, 363.
- Boice, D. C., Kuhn, J. R., Robinson, R. D. & Worden, S. P., 1981. *Astrophys. J. Lett.*, **245**, L71.
- Drake, S. A. & Linsky, J. L., 1986. *Astr. J.*, **91**, 602.
- Drake, S. A., Simon, T. & Linsky, J. L., 1989. *Astrophys. J. Suppl.*, **71**, 905.
- Dulk, G. A., 1985. *Ann. Rev. Astr. Astrophys.*, **23**, 169.
- Endal, A. S. & Sofia, S., 1979. *Astrophys. J.*, **232**, 531.
- Fix, J. D. & Spangler, S. R., 1976. *Astrophys. J.*, **209**, 503.
- Gardner, F. F., Milne, D. K., Mezger, P. G. & Wilson, T. L., 1970. *Astr. Astrophys.*, **7**, 349.
- Gilliland, R., 1985. *Astrophys. J.*, **299**, 286.
- Gray, D. F., 1989. *Astrophys. J.*, **347**, 1021.
- Hall, D. S., 1976. In: *Multiple Periodic Variable Stars*, IAU Colloq. No. 29, ed. Fitch, W. S., Reidel, Dordrecht.
- Hartmann, L., Dupree, A. K. & Raymond, J. C., 1981. *Astrophys. J.*, **246**, 193.
- Hoffleit, D. & Jaschek, C., 1982. *Bright Star Catalogue*, 4th edn, Yale University Observatory, New Haven, Connecticut.
- Kuijpers, J., 1985. In: *Radio Stars*, eds Hjellming, R. & Gibson, D. M., Reidel, Dordrecht.
- Large, M. I., Beasley, A. J., Stewart, R. T. & Vaughan, A. E., 1989. *Proc. Astr. Soc. Aust.*, **8**, 123.
- Linsky, J. L. & Haisch, B. M., 1979. *Astrophys. J. Lett.*, **229**, L27.
- Maggio, A., Vaiana, G. S., Haisch, B. M., Stern, R. A., Bookbinder, J., Harnden, F. R. & Rosner, R., 1990. *Astrophys. J.*, **348**, 253.
- Manchester, R. N., 1991. *Adv. Space Res.*, **11**, 403.
- Mills, B. Y., 1981. *Proc. Astr. Soc. Aust.*, **4**, 156.
- Milne, D. K., 1968. *Aust. J. Phys.*, **21**, 201.
- Milne, D. K. & Manchester, R. N., 1986. *Astr. Astrophys.*, **167**, 117.
- Mutel, R. L. & Lestrade, J. F., 1985. *Astr. J.*, **90**, 493.
- Parker, E. N., 1970. *Ann. Rev. Astr. Astrophys.*, **8**, 1.
- Retallack, D. S., 1983. *Mon. Not. R. astr. Soc.*, **204**, 669.
- Rutten, R. G. M., 1987. *Astr. Astrophys.*, **177**, 131.
- Rutten, R. G. M. & Pylyser, E., 1988. *Astr. Astrophys.*, **191**, 227.
- Slee, O. B., Nelson, G. J., Stewart, R. T., Wright, A. E., Innis, J. L., Ryan, S. G. & Vaughan, A. E., 1987. *Mon. Not. R. astr. Soc.*, **229**, 659.
- Slee, O. B., Stewart, R. T., Bunton, J. D., Beasley, A. J., Carter, B. D. & Nelson, G. J., 1989. *Mon. Not. R. astr. Soc.*, **239**, 913.
- Vaiana, G. S. *et al.*, 1981. *Astrophys. J.*, **245**, 163.
- Whiteoak, J. B. Z., 1991. *PhD Thesis*, University of Sydney, in preparation.