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# Radio Characteristics of Cool Stars and the HRD

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**Abstract.** We discuss statistical properties of non-flaring radio emission of a large sample of active stars and binaries. Various radio Hertzsprung-Russell Diagrams are presented.

## 1. Introduction

Radio emission is routinely observed from a number of stellar classes, yet its value as a diagnostic means has often been neglected if not dismissed. Every so often radio observations have been added to large campaigns as corollary information on variability, or as complementary illustrations that high-energy processes occur in stellar atmospheres.

But can radio emission be used as a window to access stellar activity in its own right, in a systematic and comprehensive way? Does radio emission reflect fundamental properties of stellar atmospheres much like X-ray radiation is a tracer of the coronal thermal energy?

Radio emission from stars is comparatively difficult to detect. Measuring the Sun's non-flaring radio emission at the distance of the nearest star (1.3 pc) would be a challenge for the VLA, with integration times of 10 hours at the most sensitive 3.6 cm band required for a $3\sigma$ detection.

Nevertheless, over the years a considerable archive of stellar radio detections has accumulated, in fact to an extent that systematics of the radio properties can be addressed across the Hertzsprung-Russell Diagram (HRD). We have done so by using the comprehensive *Catalogue of Radio Stars* by Wendker (1998), complemented with information from other catalogs.

## 2. What Can We Expect?

Radio emission comes in different flavors. While radiation from hot stars is probably induced in the shocks of massive stellar winds and the emission from symbiotic binaries may be related to wind collision zones, the cool stars area is dominated by radiation from magnetic atmospheres somewhat resembling the Sun's. While solar non-flaring radiation is attributed mainly to bremsstrahlung from the chromosphere or transition region and gyroresonance emission from low-lying coronal magnetic structures, what we detect from other cool stars is mostly gyrosynchrotron emission from mildly relativistic electrons trapped in coronal loops, perhaps similar to what we observe during solar flares.

We address mainly the radio behavior of *detected* stars on the *main sequence* (for special classes such as RS CVn binaries or Algols see, e.g. Drake et al. 1989; Umana et al. 1991; for dMe stars, White et al. 1989). We are interested to see whether i) this radiation shows effects of saturation, like X-ray emission, indicating that particle acceleration reaches an upper threshold for very active stars; and ii) whether radio emission depends on rotation period, $v\sin i$, mass, or spectral type of a main-sequence star.

## 3. A Radio HRD

Published information on radio stars is comprehensive enough to review a complete HRD of radio emission. A radio HRD based on Wendker (1998) is shown in Figure 1 (for other examples, see also White 1998, 1999). It comprises information on 441 stars. Only detections betwen 1–10 GHz have been considered. The symbol size gives the luminosity, derived from the logarithmically averaged fluxes of all *detections*. Clearly, some bias is introduced by i) not considering upper limits, and ii) by not considering emission mechanisms (e.g., late-type flare stars may produce short but very bright coherent flares that are energetically unimportant). The logarithmic average, however, tends to suppress outliers and represents typical luminosities reasonably well.

Special corrections were applied to Wolf Rayet stars (spectral corrections to $B-V$ values), to pre-main-sequence stars (approximate location in HRD estimated from $m_v$, $A_V$ and spectral type), and to symbiotic stars (emission assigned to the red giant). The location of many stars in the HRD is therefore somewhat tentative but should reasonably represent their class.

The usual features are recovered, i.e., the main sequence, the Hertzsprung gap, and the subgiant/giant branches. Note that the radio flux is typically stronger in the upper part of the HRD. This is both a physical and a detection limit effect. The optically luminous stars are on average farther away so that only their strongest representatives are detected at radio wavelengths. On the other hand, the diagram does suggest that higher-luminosity stars exist toward the brighter part of the HRD.

## 4. The 3-D Perspective

Figures 2–3 illustrate a pseudo-3-D view of the radio (and X-ray) HRD. The smoothed surfaces represent the *maximum radio luminosity* detected as a function of location on the HRD.[1] Figure 2a refers to all 441 detected stars. Note the plateau of luminous stars in the center; most of the contributing stars are RS CVn binaries. Also note the break along the main-sequence around $B-V=0$: This represents the activity gap among A stars. Fig. 2b shows an X-ray HRD in an equivalent representation (data from Hünsch et al. 1998a,b,1999; Berghöfer et al. 1996). Note the similarity of the diagrams.

[1] We caution that low areas may represent either absence of stars, or absence of surveyed objects, or actual low luminosity levels. Individual checks are required.

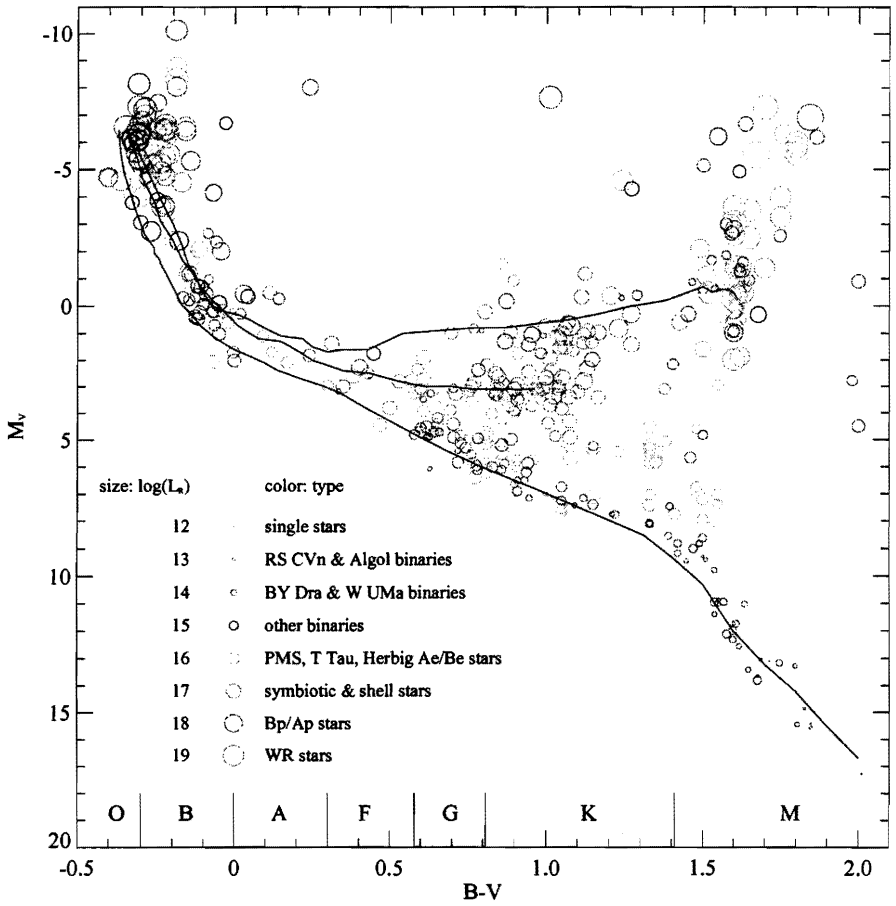


Figure 1. The Radio HRD.

Fig. 3 is based on the subsample of single stars or non-interacting binaries in which the radio emission can be well attributed to one of the sources. Three features are noteworthy:

- The envelope for the radio flux steadily increases along the main-sequence from spectral types M to G. Indication for saturation?
- The peak luminosities on the cooler main sequence are reached around spectral types G, a somewhat suprising fact given their sparse detections until recently. On the other hand, this is precisely what is known from X-rays.
- There is a clear gap around $B - V = 0$–$0.3$, i.e., A-early F stars are, with the exception of chemically peculiar Ap/Bp stars (Linsky et al. 1992), not strong radio emitters (Fig. 3). This is not due to a detection bias/low sample density as these stars have been observed but not detected at deep sensitivity levels down to $\log L_R \approx 12.5$ (e.g., Brown et al. 1990).

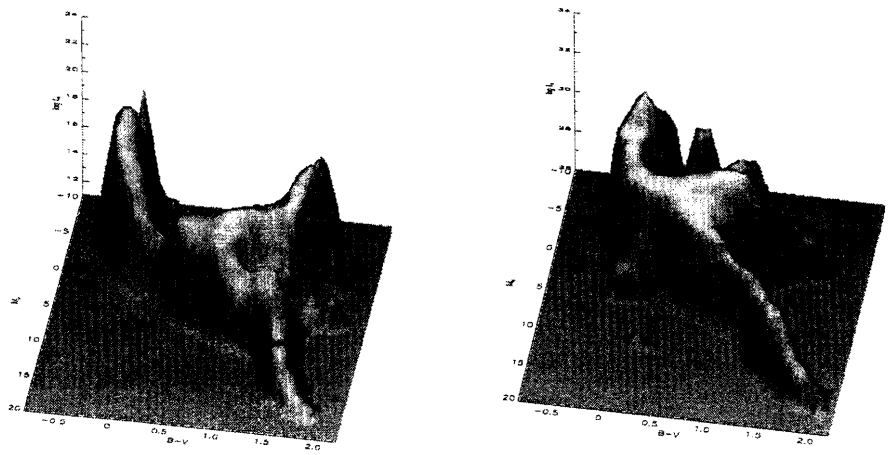

Figure 2. Maximum envelope representation of radio HRD (left) and X-ray HRD (right); complete star samples have been used.

## 5. Dependence on Spectral Class, Luminosity, and Rotation

We have collected rotation period or $v\sin i$ information from the literature (mostly from Delfosse et al. 1998; White et al. 1989 and refs therein; Strassmeier et al. 1993 and references therein; see also Stewart et al. 1988 for a related analysis) to investigate statistically which parameters determine activity in the radio regime.

Fig. 4a shows radio luminosity $L_R$ versus the bolometric luminosity $L_{\rm bol}$ of the radio-detected stars. Only stars on or very close to the MS have been considered, including binaries. Fig. 4b shows the *same* stars but for their X-ray luminosity $L_X$ instead of $L_R$ (X-ray data from Hünsch et al. 1999 and Strassmeier et al. 1993 and references therein). Two features deserve to be mentioned:

- Almost all detected radio stars are found close to the empirical X-ray saturation limit $L_X/L_{\rm bol} \approx 10^{-3}$. This is somewhat unfortunate as it indicates that *radio emission has so far been investigated mainly in X-ray saturated coronae.*
- The radio emission itself follows a saturation trend on the MS, with $L_R/L_{\rm bol} \approx 10^{-18}$ Hz. *The production of high-energy electrons saturates in active stars very much like the production of hot plasma saturates.*

To address the issue of *which parameter* is responsible for saturation, we plot in Fig. 4c normalized $L_R$ versus normalized $v\sin i$. The normalization is with $(v\sin i)_0$ expected for a star just entering the X-ray saturation regime, and with $L_{\rm bol}/10^{18}$ Hz for the same star. This normalization is necessary as $(v\sin i)_0$ depends on spectral type (a few km s$^{-1}$ for M dwarfs, but 20–30 km s$^{-1}$ for a G star). The solid curve is a saturation fit to X-ray data used by Audard et al. (2000; this conference) shifted to the radio flux regime. It smoothly connects from the unsaturated regime ($L_X \propto (v\sin i)^2$) to the saturation regime

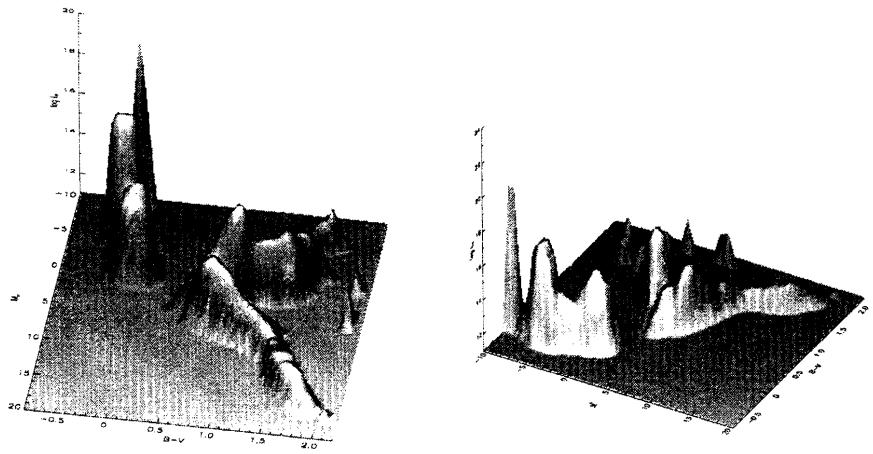

Figure 3. Maximum envelope representation of radio HRD showing single stars only.

($L_X = 10^{-3} L_{\rm bol}$). As most of the stars are close to the saturation regime, effects are subtle. The results show relatively little dependence on normalized velocity, as expected for saturation.

## 6. Conclusions

A large sample of cool star radio detections begins to statistically unveil trends so far known in the X-ray regime. In particular,

- magnetically induced non-thermal radio luminosity on cool stars saturates similarly as X-ray radiation does, with saturation at $L_R/L_{\rm bol} \approx 10^{-18}$ Hz$^{-1}$, at least on the MS.
- Therefore, the largest magnetically induced radio luminosities on the cool main sequence are found at spectral type G.
- The peak luminosity decreases toward early F and basically disappears within spectral class A, with the prominent exception of the magnetic Ap/Bp stars.

Most radio detections refer to stars that are within or close to the X-ray saturation regime. Although this appears as a bias at first sight, it may well be that saturation favors the presence of radio emission.

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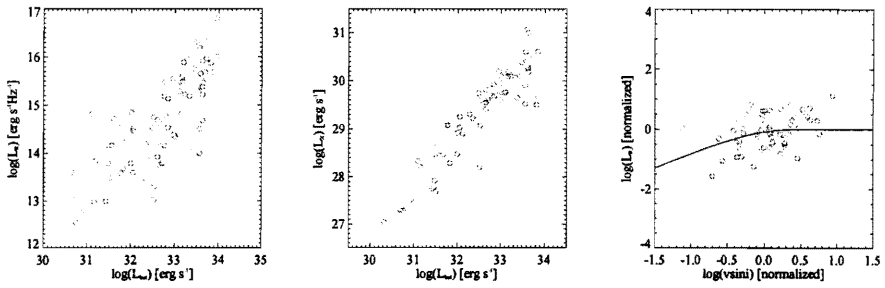


Figure 4. Correlations between (*left*) $L_{\rm R}$ and $L_{\rm bol}$; (*middle*) $L_{\rm X}$ and $L_{\rm bol}$; (*right*) normalized $L_{\rm R}$ and $v\sin i$.


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