The X-Ray and Radio Emission Properties of Rapidly Rotating Cool Giants

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Abstract. We have conducted a radio continuum and X-ray survey of 85 'astrophysically single' cool giants and subgiants for which measured $v \sin i$ and/or rotational period measurements indicate rapid rotation. The radio and X-ray luminosities were obtained by combining the measured fluxes with distances obtained from the *Hipparcos* Catalog (available for 75% of the sample), or from their MK spectral classifications (for the remaining 25%). As expected, the X-ray luminosities L_x and efficiencies L_x/L_{bol} are moderate to high for this sample of stars, with mean values of $\log L_x$ and $\log L_x/L_{bol}$ of 30.0 ± 0.8 and -5.5 ± 1.0, respectively, and maximum values of $\log L_x$ and $\log L_x/L_{bol}$ of 31.8 and -3.0 (the 'saturation limit' for coronae), respectively. Detected radio emission is quite uncommon, only 15% of this sample having been detected, and correlates well with X-ray efficiency: essentially all stars with $log L_x/L_{bol} \geq -4.0$ are detected radio sources, possibly suggesting that significant nonthermal radio emission requires a threshold coronal efficiency. We compare the properties of this sample of evolved single stars with those of similar stars in binary systems having similar rotation rates, and find some evidence that the single stars are less active than binary stars of the same rotation rates.

1. Introduction

Many papers have been written on the so-called 'Activity-Rotation Connection' for late-type stars and its general correctness for all stars having convective envelopes, i.e. roughly spectral types F and later, has been demonstrated, with the exception of the shallow-convection zone, early F-type stars. In the simplest terms, it implies that the more rapidly a star rotates, the more 'active' the star's

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chromosphere, transition region, and corona will be. (In detail, the most appropriate quantitative measures of rotation and activity, e.g., rotational period P_{rot} or Rossby number Ro, luminosity or surface flux, have been 'actively' debated over the last two decades, and we will return to some of these distinctions later).

It is important to realize that not all types of late-type stars have had their rotational and activity properties examined: most studies have been limited to either (single or binary) main-sequence stars or to evolved giant stars in synchronized binary systems, such as the RS CVn and Algol classes. In particular, the behavior of single giants and subgiants has not been extensively studied. It is thus the aim of the present paper to study the rotation/coronal activity connection in **single, evolved** stars, ranging from moderately active field giants such as β Cet up to and including the most extreme FK Comae type giants, using the (presumably nonthermal) radio continuum emission and (presumably thermal) X-ray emission of these stars as our proxy indicators of 'coronal activity' In detail, we want to (i) compare the properties of these stars with those of similarly evolved stars in binary systems such as the longer-period RS CVn binaries: are they different, e.g., do the single stars lie below the binaries in activity-rotation relations as might occur if binarity *per se* is a factor, e.g., due to star-star magnetic field interactions? (ii) see if there are any stars that are distinct from the general population, e.g., stars that are radio-strong or radio-weak for their X-ray luminosity levels, or stars that are X-ray or radio deficient for their rotation rate or Rossby number, (iii) determine whether there is any evidence favoring, for example, Rossby number over rotational period (or its inverse) as a characterization of rotational rate.

2. The Sample of Rapidly Rotating Single Giants and Subgiants

We have assembled a set of 85 giants and subgiants of spectral types G and K which have either photometrically determined rotation periods or measured $v \sin i$ values that are significantly higher than 'normal' stars of this type, plus a few others added for comparison, e.g., the rapidly rotating F5 III star $29\pi^2$ Peg and the slowly rotating, but extensively spotted G8 III-IV star HR 1362. Measured rotation periods range from ≤ 1 day (claimed for 24 UMa and LW Hya, the central star of the planetary nebula Abell 35) to 307 days for HR 1362. Measured $v \sin i$ values range from 1.5 km s^{-1} (HR 1362) to 160 km s^{-1} (FK Com). 79 of the 85 stars (93%) in the sample have measured or inferred rotational periods in the range from 1 to 150 days that corresponds to the classical and long-period RS CVn systems. 65 of the 85 stars (76%) have statistically significant trigonometrical parallaxes in the Hipparcos Catalog from which we derived distances; for the other stars, distances were derived from either their spectroscopic parallaxes or from their membership in an open cluster.

We have tried to exclude all stars with significant radial velocity variability where the rapid rotation is believed to result from spin-orbital coupling, e.g., RS CVn binaries, but have not excluded giants in wide binary systems where they can be treated as 'astrophysically single' stars. Thus, we have included 5 stars with known white dwarf or hot subdwarf companions (LW Hya; IN Com = HD 112313, the central star of the planetary nebula LoTr 5; HD 128220; DR Dra; and V832 Ara), since all of these are believed to be wide binaries.

3. The X-ray and Radio Continuum Data

The X-ray data were primarily taken from the *ROSAT* PSPC All-Sky Survey Bright Source Catalog (RASSBSC) (Voges et al. 1999), supplemented by data from pointed *ROSAT* and *Einstein* observations. We have used conversion factors of 7×10^{-12} and 2×10^{-11} erg cm^{-2} ct^{-1} for the *ROSAT* PSPC and *Einstein* IPC, respectively, to convert observed count rates into fluxes. We have assumed an upper limit of $f_x = 3.5\times10^{-13}$ erg s^{-1} cm^{-2} for those stars for which no X-ray detections are available, this being the canonical RASSBSC threshold. These upper limits need to be confirmed by a direct inspection of the RASS event data for these fields, in case the apparent non-detection is due to confusion or misidentification, or to lack of exposure of the particular part of the sky. For a star at a typical distance of 200 pc, this upper limit corresponds to a threshold X-ray luminosity $L_x = 10^{30.2}$ erg s^{-1}, which is approximately the same as the X-ray luminosity of the nearby active giants Capella or β Cet. The radio continuum data were taken either from the literature or were obtained in Australia Telescope Compact Array (ATCA) and NRAO Very Large Array (VLA) observing programs, and are generally either 3.6 cm or 6 cm data. Typical upper limits are 0.6 and 0.25 mJy for the ATCA and VLA respectively. For a star at a typical distance of 200 pc, these upper limits correspond to a threshold radio continuum luminosity $L_{rad} = 10^{16.3}$ erg s^{-1} Hz^{-1}, which is 500 times the radio luminosity of Capella. Notice that the effective X-ray 'horizon' is thus much more distant than the radio 'horizon', and this bias means that only the truly 'superactive' stars can be detected, in general, at radio wavelengths.

4. The Preliminary Results

This study is an ongoing one and the results are still preliminary, but some of the initial results are summarized below:

- 47 of the 85 stars (55%) in our sample have been detected as X-ray sources, implying that X-ray emission is prevalent in this sample, with a mean $\log L_x = 30.6\pm0.6$ for the 47 detected stars which is much greater than that seen in, for example, volume-selected samples of cool giants (cf. Hünsch *et al.* 1998). Taking account of the 38 X-ray upper limits using a maximum likelihood technique, we estimate that the mean $\log L_x$ for the full sample is 30.0 ± 0.8 which is still significantly higher than the average for GK giants and subgiants in the solar neighborhood. There are 14 stars in the sample with $\log L_x \geq 31.0$, the most X-ray luminous star being V2253 Oph (HD 152178) with $\log L_x = 31.8$.

- X-Ray efficiencies $\log L_x/L_{bol}$ vary between -7 and -3, with a mean $\log L_x/L_{bol}$ of -4.8 ± 0.8 for the 47 detected stars, and of -5.5 ± 1.1 for the whole sample. Nine stars in the sample have $\log L_x/L_{bol} \geq -4$, the most X-ray efficient star being NGC 188 III-9, which has $\log L_x/L_{bol} = -3.0$. This implies that few evolved stars have values close to the 'saturation' limit of $\log L_x/L_{bol} \sim -3.0$.

- We have divided the sample of stars into 4 ranges of absolute magnitude, and note that stars with $M_V \leq -1.0$, i.e, 'bright giants' of equivalent

MK luminosity classes II and II-III, have a very low X-ray detection rate (2/18). All but one of these 18 stars were included in our sample based on their having 'high' $v \sin i$ values of between 4 and 10 km^{-1}. The failure to detect more than 2 of these stars implies either (i) the rotation-activity relation does not apply to bright giants, the evolutionary descendants of stars which probably lacked significant convection zones during their main-sequence lifetimes, or (ii) their rotation rates have been overestimated and/or confused with macroturbulence. One of the two X-ray detected bright giants, 37 Com, has a fairly high $\log L_x = 30.7$ and appears to be a somewhat cooler (G9 II-III) doppelganger of β Dra (G2 II).

- We have studied in some detail the behavior of X-ray activity as a function of rotation in this sample, using the Maximum Likelihood technique discussed in Drake, Simon & Linsky (1989, 1992) to take account of the large number of X-ray upper limits in our sample. We have reached the following conclusions: (i) As expected based on other samples (cf. the RS CVn sample of Drake, Simon & Linsky 1989), the correlations using L_x/L_{bol} as a measure of activity are more significant than those in which L_x is used, e.g., $L_x/L_{bol} \propto P_{rot}^{-0.95\pm0.21}$ compared to $L_x \propto P_{rot}^{-0.46\pm0.18}$. We expected that, based on previous studies of samples of dwarf stars, the X-ray activity would correlate even more strongly as a function of a Rossby-number type parameter (P_{rot}/τ_c, where τ_c is the convective turnover time) than with the rotational period *per se*. We have crudely estimated Rossby numbers for the stars in our sample by combining the measured rotational periods (or the values inferred from the $v \sin i$ values for the stars lacking directly measured periods) with convective turnover times estimated from the Noyes et al. (1984) dwarf relation and the rough correction factors for luminosity class suggested by Henry et al. (1995), e.g., a subgiant and giant have convective turnover times 2 and 4 times longer than a main-sequence star of the same color. We find no improvement in the correlations using Rossby number instead of P_{rot}, e.g., $L_x/L_{bol} \propto \mathrm{Ro}^{-1.09\pm0.27}$. We suspect that is likely due to our Ro estimates being systematically too small (i.e., due to our convective turnover times being too large) for the earlier type stars, e.g., the rapidly rotating thin convective-zone giant π^2 Peg (F5 III, $v \sin i = 139$ km s^{-1}, $\log \mathrm{Ro} \sim -0.9$) is predicted by the above correlations to be a fairly strong X-ray source, but in fact is not detected, with $\log L_x < 29.4$. Clearly, to do a better analysis of this will require a proper calculation of the Rossby numbers for these evolved stars.

- We have compared the above correlations for **single** evolved active stars with the results of a similar analysis for evolved stars in active binaries. Interestingly, one systematic difference we find is that the latter sample of binaries appears to be about an order of magnitude more active when comparing stars of the same rotational period, even though the slopes of the activity-rotation relations are similar: $L_x/L_{bol} \sim 8 \times 10^{-4} P_{rot}^{-0.86\pm0.10}$ for the **binary** stars compared to $L_x/L_{bol} \sim 8 \times 10^{-5} P_{rot}^{-0.95\pm0.21}$ for the **single** stars. This difference, if confirmed, would indicate that binarity *per se* increases stellar activity levels, but we are somewhat skeptical of its reality and suspect that it is mostly due to selection effects, e.g., the active single giants sample contains more of the mostly X-ray-underluminous early G-type stars than the active binaries sample does. Thus, we believe that the effects of binarity are still an open question.

- As recently discussed by Strassmeier et al. (1999), the G8 giant HR 1362 = EK Eri, while slowly rotating (P_{rot} = 307 days), appears to be magnetically active. In fact, we find its X-ray luminosity to be reasonably high, $\sim 10^{30}$ erg s^{-1}, which is in agreement with their findings. Again, using the correlations mentioned above, we would predict an X-ray emission level for HR 1362 that is $50 - 100$ times weaker than this observed value, so it is very anomalous. It would be interesting to see if there are other evolved stars of low intrinsic rotation which have similarly discrepantly high coronal emission levels. Strassmeier et al. speculate that HR 1362 may be the evolutionary descendant of an Ap star having a kiloGauss magnetic field when on the main-sequence. (We parenthetically note that their estimate of 1 in 100-1000 stars on the upper main-sequence having such strong magnetic fields is a rather considerable underestimate, in our opinion, and that, based on the observed fractions of 'magnetic' chemically peculiar stars, we expect a much higher fraction of 1 in 10-30 stars, depending on the minimum value of the magnetic field adopted).

- Only 13 of the 54 stars which have been observed in the radio continuum have been detected, reflecting to some extent the difference between the radio and the X-ray horizons for active stars. Essentially all stars with $log L_x/L_{bol} \geq -4.0$ are detected as radio sources, suggesting either that significant nonthermal radio emission requires a threshold coronal efficiency, or that there is a steeper than linear dependence of radio emission on X-ray emission (as noted below, such a dependence has indeed been found for RS CVn binary stars). Excluding Capella, whose weak radio continuum emission ($\log L_{rad} = 13.6$, where L_{rad} has units of erg s^{-1} Hz^{-1}) is believed to be coronal free-free and/or chromospheric thermal emission, the stars detected in the radio range have radio luminosities similar to those found for RS CVn binary stars, i.e., $15.8 \leq \log L_{rad} \leq 18.0$, and are presumably nonthermal radio emitters like the RS CVns. Two exceptionally strong radio emitters are southern stars in which tremendous radio flares were observed which reached levels as high as ever observed in any class of active late-type stars, e.g., YY Men reached $\log L_{rad} = 19.5$ and CF Oct reached $\log L_{rad} = 18.6$. The radio detections and non-detections are generally consistent with the values expected from their X-ray luminosities, assuming that the relation found for RS CVn binaries, viz. $\log L_{rad} = 1.372 \times \log L_x - 26.4$, applies. Two exceptions appear to be LW Hya and HD 112313, which appear to be radio-strong for their X-ray luminosity level (or alternatively X-ray weak for their radio luminosity level): interestingly both of these stars are central stars of planetary nebulae, suggesting a possible evolutionary factor.

- As noted by Hagen & Stencel (1985), single GK giant stars with rotation rates comparable to FK Com ($v \sin i$ = 160 km s^{-1} or P_{rot} = 2.40 days) are indeed very rare, although at least one rather similar star (NGC 188 III-9: P_{rot} = 2.67 days) has since been discovered. Note that the radio and X-ray activity levels of FK Com, while high (e.g., $\log L_x = 31.1$), are not excessively so compared to the sample as a whole (this may indeed be due to the fairly early G2 spectral type of FK Com, which gives it a Rossby number similar to those of the more slowly rotating G5-K0 giants in our sample).

5. Conclusions

Rapid rotation, as measured by either the rotational period or a Rossby-type parameter, and activity, as measured by either X-ray or radio continuum emission, do indeed appear to be closely correlated in this sample of astrophysically single, rapidly rotating, single giants and subgiants. There appears to be a discernible difference between the rotation-activity relation found for this sample and for that of a somewhat larger sample of active evolved stars in RS CVn binaries, in that the binary stars are 10 times more active for the same rotation rate. However, there are some potentially strong selection effects which we have still to investigate in detail before this difference can be conclusively confirmed. If true, it would suggest that there is an additional component of activity which is caused by binarity *per se*, and that the activity level is not indifferent to the process which produces rapid rotation in evolved stars.

There are some interesting possible deviations from the general relationships that we have found, including (i) 2 central stars of planetary nebulae which appear X-ray deficient compared to the level that would be predicted from their radio emission, and (ii) the very slowly rotating G8 III-IV star HR 1362 which, despite its slow rotation, has a fairly high level of X-ray emission. These exceptions to the rule may be telling us that, in at least some stars, the current coronal activity level is dependent not only on the current rotation rate and convective envelope timescale, but also on their past and/or present evolutionary states.

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