X-RAY/MICROWAVE RELATION OF DIFFERENT TYPES OF ACTIVE STARS

MANUEL GÜDEL\footnote{1} AND ARNOLD O. BENZ\footnote{2}

Received 1992 September 28; accepted 1992 December 21

ABSTRACT

Coronal active stars of seven classes between spectral types F and M, single and double, are compared in their quiescent radio and X-ray luminosities $L_R$ and $L_X$. We find, largely independent of stellar class, $\log L_X \lesssim \log L_R + 15.5$. This general relation points to an intimate connection between the nonthermal, energetic electrons causing the radio emission and the bulk plasma of the corona responsible for thermal X-rays.

The relation, observed over six orders of magnitude, suggests that the heating mechanism necessarily involves particle acceleration. We derive requirements for simple models based on optically thin gyrosynchrotron emission of mildly relativistic electrons and thermal X-rays from the bulk plasma. We discuss the possibility that a portion of the accelerated particles heats the ambient plasma by collisions. More likely, plasma heating and particle acceleration may occur in parallel and in the same process, but at a fixed ratio.

Subject headings: stars: coronae — stars: late-type — radio continuum: stars — X-rays: stars

1. INTRODUCTION

Soft X-ray observations of several classes of late-type main-sequence stars (spectral type F–M) as well as some (sub-)giants have provided conclusive evidence for the presence of $10^6$–$10^7$ K coronal material around these stars, largely independent of spectral type (e.g., Vaiana et al. 1981). It is thought that, as is the case for solar active regions, the hot material is magnetically confined in closed coronal structures (magnetic loops).

Radio observations have provided evidence of high-level coronal activity on many of these stars, either in the form of strong flares, or steady or slowly varying (“quiescent”) microwave radiation. The steady radio emission of dMe stars is commonly attributed to gyrosynchrotron radiation of mildly relativistic electrons (e.g., Kundu & Shevgaonkar 1985; Pallavicini, Willson, & Lang 1985). Model calculations by White, Kundu, & Jackson (1989b) show that the typical flat dMe spectra are best reproduced with electrons having a power-law energy distribution with spectral index $\delta$ around 3. In the case of RS CVn stars, Drake, Simon, & Linsky (1989) interpret the quiescent radio luminosity $L_R$ as being due to thermal gyrosynchrotron emission of a hot component $T = 5 \times 10^7$ K in $B = 210$ G fields. However, almost flat spectra as well as VLBI observations support a nonthermal gyromagnetic origin of this radiation (Mutel et al. 1985) with $\delta \approx 3.5$ (Morris, Mutel, & Su 1990). Generally, the spectra of many active stars seem to become optically thin at frequencies above typically 5 GHz.

The interrelation between these two coronal emissions has been controversial. Kundu et al. (1988) found little correlation between microwave and X-ray fluctuations or flares on four selected dMe targets over a few hours. Based on larger dMe samples studied for nonflaring emissions, Bookbinder (1987) found a dependence between the radio and X-ray luminosities $L_R$ and $L_X$. The existence of such a relation was questioned by Cailart, Drake, & Florkowski (1988), who considered sensitivity limits, long-term variations, and physical reasons to explain their result. White, Jackson, & Kundu (1989a), however, found that for dMe stars of a given spectral type, the detected radio sources tend to be those with the highest X-ray fluxes. For the RS CVn class, Drake et al. (1989) reported a distinct relation between $L_R$ and $L_X$. With the advent of ROSAT, new samples have become available for correlation studies. Using the highly sensitive VLA X-band and ROSAT data that were obtained simultaneously, a linear correlation between $L_R$ and $L_X$ was found for M dwarfs (Güdel et al. 1993a).

In this Letter we propose a different test on the existence of a physical relation between nonthermal and thermal particle energies in the coronae of active stars. Instead of comparing small variations on a few individual stars or similar objects within a stellar class, we compare the luminosities of very different classes of stars ranging over many orders of magnitude. We solely require that our stellar classes exhibit magnetically governed coronal activity. We hypothesize that energy release and transformation processes are general coronal characteristics of active stars largely independent of stellar type.

2. OBSERVATIONAL DATA

We summarize X-ray and radio properties of several classes of magnetically active stars and a few surveys relevant for our investigation below. Hybrid stars and Bp/Ap stars have been excluded here. Hybrids do show chromospheric/coronal activity (e.g., Brown et al. 1991), but they are also wind sources. Bp/Ap stars possess strong (kG) magnetic fields; their stable dipole configuration, however, differs from a classical (solar-like) corona (e.g., Linsky, Drake, & Bastian 1992).

A recent campaign addressing coronal diagnostics of M dwarfs used ROSAT and the VLA for (near-)simultaneous observations of about 20 targets. The reported dMe stars occupy the range $27 \lesssim \log L_X \lesssim 29.6$, where $L_X$ is in erg s$^{-1}$ and $L_R$ is in ergs s$^{-1}$ Hz$^{-1}$ (Güdel et al. 1993a,b).

A class of active main-sequence K stars has also been detected in both energy regimes (Güdel 1992). The K0 V star AB Dor is the best studied example of a young star on its last stage of evolution toward the main sequence (e.g., Lim et al. 1992; Collier Cameron et al. 1988).

BY Dra binaries consist of two late-type (spectral type K or M) main-sequence stars in a close orbit, with orbital periods of

\footnotesize{1} Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, CO 80309-0440.
\footnotesize{2} Institute of Astronomy, ETH Zentrum, CH-8092 Zürich, Switzerland.

© American Astronomical Society • Provided by the NASA Astrophysics Data System
RS CVn binaries typically consist of a late-type main-sequence star and a G or K (sub-)giant. Drake et al. (1989, 1992) found a significant correlation between $L_R$ and the rotation velocity of the primary in the range $28.8 \leq \log L_X \leq 32.2$.

FK Comae-type stars are single, rapidly rotating ($v \sin i \geq 100 \text{ km s}^{-1}$) late-type (G-K) giants or subgiants (Bopp & Stencel 1981), believed to have resulted from the coalescence of close (contact) binaries when one of the companions evolved into a giant. They are found in the range $30.9 \leq \log L_X \leq 32$.

Post-T Tau stars (PTTS) are low-mass pre-main-sequence stars that have evolved beyond the classical T Tau phase. Many are strong X-ray sources ($30 \leq \log L_X \leq 31$) and highly variable, flaring nonthermal radio sources. We consider the lowest recorded X-ray fluxes to approximate the “quiescent levels” (White, Pallavicini, & Kundu 1992, and references therein).

Algol binaries are also considered here. However, at least one of the two components in these systems is of early spectral type, and strong mass transfer may be involved.

In Figure 1 we correlate $L_R$ and $L_X$ of individual radio and X-ray detected stars of all above stellar classes. Most X-ray luminosities refer to Einstein and ROSAT, with exceptional EXOSAT values. The difference due to the different energy ranges is expected to be minor for a $10^7 \text{ K}$ thermal line spectrum (of order 10%). The quantity $L_R$ mostly refers to 6 cm wavelength, and exceptionally to 3.6 cm. Again, due to typically rather flat spectra, the difference is negligible. The scatter is strongly dominated by intrinsic luminosity properties and slow temporal variations of the coronal emission (for RS CVn binaries, e.g., see Drake et al. 1989; for most objects, observations of $L_R$ and $L_X$ were not simultaneous).

Evidently, $L_X$ is positively correlated with $L_R$ over five orders of magnitude across all considered stellar classes. The dMe(e), dKe(e), and BY Dra stars occupy the lower left portion of the diagram, where $\log L_X \leq \log L_R + 15.5$. The other classes define the continuation toward higher luminosities. The more luminous half of the diagram is somewhat offset toward higher radio luminosity, but evidently fulfills $\log L_X \leq \log L_R + 15.5$ with very few exceptions. We will call stars having $\log L_X < \log L_R + 15.5$ “microwave-rich” or “X-ray-poor.” A rough integration of $L_R$ over the relevant microwave range ($\approx 0.1 \text{ GHz}$) yields $L_X/L_{R,\text{tot}} \approx 10^{-5}$. It was shown both for the RS CVn sample and the dMe stars that a distance scaling of fluxes introduced by detection limitations is not responsible for the reported correlation (Drake et al. 1989; Güdel et al. 1993b).

3. DISCUSSION

The persistent trend of a positive correlation between $L_X$ and $L_R$ (close to proportionality) over a large range of luminosities is valid for a variety of different stellar classes independently of age (young main-sequence stars to evolved giants), spectral class (F, G, K, and M), binary (single stars or close binaries), rotation (periods between 12 hr and $\approx 100$ days), or photospheric/chromospheric activity (spotted vs. unspotted stars, emission-line vs. non-emission-line stars).

VLBI observations suggest a size of order of $10^{12} \text{ cm}$ for the magnetosphere of RS CVn binaries (Mutel et al. 1985) and less than $8.7 \times 10^{10} \text{ cm}$ for a dMe star (Benz & Alef 1991). If the thermal or the nonthermal energy density were approximately similar for all stars, we would estimate a ratio of $10^3$ between the volumes of the two coronae and thus their luminosities; this could in part explain the wide range of observed luminosities. The marked deviation of the high luminosity, microwave-rich stars, especially the complete RS CVn class, is likely a result of larger magnetospheres, causing longer trapping times for the radio-emitting high-energy particles.

What are the conditions for a constant radio/X-ray ratio? The quiescent emission of synchrotron radiation requires the continuous presence of nonthermal electrons, while X-rays are emitted by the thermal bulk of typically $10^8$ to a few times $10^9 \text{ K}$. For optically thin radio emission ($\nu \gtrsim 5 \text{ GHz}$), the radio luminosity emitted into a half-sphere is

$$L_R = 2\pi n \nu R^2 \text{ ergs s}^{-1} \text{ Hz}^{-1},$$

where $R$ is the radio source volume. The density of nonthermal electrons will be assumed to be distributed in energy according to a power law,

$$n(\epsilon) = \frac{(\delta - 1) \epsilon}{\epsilon_0} \frac{n_0}{\epsilon_0} \left( \frac{\epsilon}{\epsilon_0} \right)^{-\delta} \frac{1}{\text{ cm}^3 \text{ erg s}^{-1}}.$$

A lower cutoff at $\epsilon_0 \approx 10 \text{ keV} = 1.6 \times 10^{-8} \text{ ergs}$ is compatible with most acceleration processes proposed for stellar coronae and with solar flare observations. We keep $\epsilon_0$ fixed at $10 \text{ keV}$ in the following considerations. It is not a sensitive value for synchrotron emission since the latter becomes appreciable only at higher energies. Equation (2) is normalized by $n_0$, the number density of electrons with energy above $\epsilon_0$. We assume a homogeneous source for simplicity. The gyrosynchrotron emissivity is approximately given by Dulk & Marsh (1982)

$$\eta \approx 3.3 \times 10^{-24} B \epsilon^{-0.52} (\sin \theta)^{-0.43} \frac{\nu}{\nu_b}^{1.22 - 0.90 \delta},$$

where $\theta$ is the distance (in cm s$^{-1}$ sr$^{-1}$).

$$\equiv \theta(B, \gamma, \nu, n_0 \epsilon^8 \text{ ergs s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-3} \text{ sr}^{-1}),$$

where $\theta(B, \gamma, \nu, n_0 \epsilon^8 \text{ ergs s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-3} \text{ sr}^{-1})$.
where \( v_g \) is the electron gyrofrequency and \( \theta \) is the angle between the line of sight and the magnetic field.

In a steady-state situation, the density of nonthermal electrons is given by

\[
n(e) = \frac{N(e)}{V_R} \tau(e),
\]

where \( N(e) \) is the total number of electrons of energy \( e \) accelerated per unit time, and \( \tau(e) \) is the electron lifetime. Let

\[
N(e) = N_0 \left( \frac{e}{e_0} \right)^{-\kappa},
\]

\[
\tau(e) = \tau_0 \left( \frac{e}{e_0} \right)^{\alpha}.
\]

With equation (4), the power-law index of the electrons (eq. (2)) is \( \delta = \kappa - \alpha \).

Let \( a \) be the fraction of the energy that goes into accelerated particles, and \( b \) the fraction of the total coronal energy ultimately radiated into the observed X-ray band. Since some of the thermal energy is lost by conduction and other processes, \( b < 1 \). Then, X-rays are related to the total energy input

\[
\dot{E} = \frac{1}{a} \int_{e_0}^{\infty} N(e) e \, de = \frac{1}{b} L_X.
\]

Using equations (1)–(7), the relation between \( L_R \) and \( L_X \) becomes

\[
L_R = 2 \pi \delta B_v \nu \delta B_0 a \tau_0 \left( \frac{e}{e_0} \right) \left( \frac{\delta - 1}{\delta + 1} \right) L_X,
\]

where we require \( \delta > 1 \) and \( \alpha > 2 - \delta \) for convergence. Equation (8) is general and includes different possible scenarios. Let us select typical parameters for stellar observations, viz. \( \delta = 3 \) (implying \( \alpha > -1 \), \( \nu = 5 \) GHz, and \( \theta = 30^\circ \); then

\[
L_R = 9.6 \times 10^{-23} B^2 \frac{a}{b} \tau_0 (\alpha + 1) L_X.
\]

Figure 1 suggests numerical relations between \( a, b, \tau, \) and \( B \) for active stars:

\[
B^2 \frac{a}{b} \tau_0 (\alpha + 1) \approx \begin{cases} 3.3 \times 10^6 & \text{dMe, dKe, BY Dra} \\ 2 \times 10^7 & \text{RS CVn, Algols, PTTS, FK Com} \end{cases}
\]

Two scenarios are possible: If the acceleration efficiency \( a \) is close to unity, the nonthermal electrons first emit a small fraction of the total kinetic energy as synchrotron radiation before they lose most of their energy by collisions, thereby heating the X-ray emitting corona (“causal relation” between nonthermal and thermal energy). It is unknown whether fully efficient accelerators are realized in nature.

The other scenario implies a common energy release, most of it heating the corona by thermal processes (e.g., Ohmic heating), and a much smaller fraction \( a \) accelerating particles. Some of the latter energy may also end up as heat, but this is negligible. Therefore, the thermal plasma and nonthermal electrons radiate independently (“common origin” scenario; e.g., Mullan 1985; Holman 1986). This scenario can explain the relation found by assuming that coronal heating in active stars necessarily implies electron acceleration to relativistic energies. The fraction between thermal and nonthermal energy release is the crucial, but unknown number. It is unclear whether it can be constant over many different types of stars.

The lifetime \( \tau \) (or \( \tau_0 \) and \( \alpha \)) which is relevant here for the gyrosynchrotron emitting high-energy particles, depends on the process that scatters energetic electrons into the loss-cone of the trapped particle velocity distribution, such as collisions, whistler wave instability, or cyclotron maser action. Their effects on the relation between trapping time and particle energy are opposite. As an example, let us assume \( \tau(e) = \text{constant (i.e., } \alpha = 0 \) and use solar active region and flare values for \( B (\approx 100 \) G) and \( a/b \) (order of unity; Dennis 1988; Withbroe & Noyes 1977). Equation (10) then would require \( \tau \approx 40 \) s for dMe(e), dKe(e), and BY Dra stars. The lifetime is an average over the time of flight of the particles that are lost immediately (moving parallel to the field lines) and the trapped particles temporarily residing in a lower density plasma. The estimated values for \( \tau \) are compatible with the minimum observed time scale of variations in the “quiescent” emission (e.g., Jackson, Kundu, & White 1989). For the halo of RS CVn binaries, \( B \) can be as low as \( \approx 10 \) G (Mutel et al. 1985). Then, from equation (10), \( \tau \) is of order of one day, compatible with observed long time scales (e.g., Massi & Chiuderi-Drago 1992; Catalano et al. 1986).

If \( a/b \) indeed attains a characteristic value on several stellar classes, then (for \( \delta \approx 3 \), as typically observed) \( B^{2.48} \tau_0 \approx \text{constant} \). This would approximately be satisfied for particles losing their energy wholly by synchrotron radiation as has been proposed for electrons in the halo structure of RS CVn stars (Mutel et al. 1985). More likely for active coronae of single stars, characteristic \( B \) and \( \tau \) could both be roughly constant. The energy density of \( B \) at the footpoints of magnetic loops cannot exceed the photospheric thermal pressure, which varies by less than an order of magnitude between F and M main-sequence stars; thus, maximum coronal magnetic fields, where most of the synchrotron radiation originates, can be expected to be of similar strength.

If the slope = 1 regression continues in Figure 1 to even weaker stars, the quiet Sun (log \( L_X \approx 10.7 \), log \( L_X \approx 27 \)) stands out as a clearly radio-underluminous star. Its lack of “quiescent” synchrotron emission is the obvious reason for this behavior. Therefore, the nonflaring solar corona, being extremely weak and inactive, does not fit into the above scenario of heating and particle acceleration in active stars. Exceptions may be solar flares, where a proportionality between peak radio and X-ray fluxes has been found (Drake et al. 1989), although the heating mechanism during flares is under debate (Dennis 1988).

The general relation between radio and X-ray luminosities of stars suggests that the heating of active coronae and particle acceleration are closely linked, reminiscent of solar flares. Efficient electron acceleration seems to be a necessary ingredient of the heating process of active stellar coronae. A more detailed study of the physical process involved in this relation is beyond the scope of this paper.

We acknowledge helpful comments by G. A. Dulk, M. J. Aschwanden, S. M. White, and the anonymous referee. This work was supported by Swiss National Science Foundation grants 8220-033360 and 20-34045.92, NASA grants NAG5-1987, through the University of Colorado, and W17772, through NIST.
REFERENCES


Lim, J. 1992, private communication


McCluskey, G. E., Jr., & Kondo, Y. 1984, PASP, 96, 817


© American Astronomical Society • Provided by the NASA Astrophysics Data System