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Steady Radio Emission from Stars: Observations and Emission Processes

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Abstract. I describe four important emission mechanisms that are used to explain nonflare cm-wave radio emission and the conditions under which each of these mechanisms can be important. I propose that the surprising correlation between thermal X-ray and nonthermal radio emission can be understood as continuous acceleration of electrons in the "sub-Dreicer" regime that occurs in the hot coronae of active stars but not in the relatively cool corona of the Sun. This may explain the absence of a solar-stellar connection at radio wavelengths.

1. Is There a Solar-Stellar Connection at Radio Wavelengths?

A large body of evidence acquired over the last 30 years from ground-based and space-based observatories demonstrates that most phenomena and physical processes occurring in the outer atmosphere of the Sun are not unique, but rather are typical of stars with convective zones and dynamic magnetic fields. In short, there is a solar-stellar connection in which phenomena observed with high spatial and temporal resolution on the Sun are useful prototypes and models for understanding stellar observations. By observing the energy range and time scales of such phenomena on late-type stars, one can understand the solar phenomena within the context of stars with different masses, ages, chemical compositions, rotation rates, magnetic fields, and other properties.

At optical and infrared wavelengths where thermal emission from the photosphere dominates, the solar spectrum differs only subtly from those of other G-type dwarfs because of different rotation rates and chemical compositions. The solar ultraviolet emission line spectrum formed in the chromosphere and transition region is qualitatively similar to what the IUE and HST/GHRS satellites typically observe in late-type dwarfs, G0–K1 giants, and active binary systems, but with one major difference. The solar luminosity in chromospheric emission lines (e.g., Mg II h and k) and transition region lines (e.g., C IV 1548, 1550 Å) is close to the minimum detected in the least active stars – the so-called basal flux rate. On the other hand, young and rapidly rotating stars can have luminosities in these lines as much as 1000 times larger than is typically observed on the quiet Sun. This indicates that nonthermal heating rates can be 1000 times larger in these stars than in the quiet Sun on a spatially averaged basis, and that there are much larger covering factors for active regions (plages) where the heating process is definitely magnetic rather than acoustic.

Soft X-ray emission from the solar corona at a luminosity level $L_x \approx 10^{27}$ ergs s^{-1} is also near the bottom of a distribution extending up to $L_x \approx 10^{31}$ ergs s^{-1}. Soft X-ray emission is observed from dwarf stars between spectral types A7 and M8 and also from OB stars, although shocks in their winds likely heat the X-ray emitting plasma. Soft X-rays from the Sun and late-type stars consist of thermal free-free and bound-free emission from a magnetically heated plasma. Very inactive stars like the Sun have coronal plasma temperatures in the (1–2)$\times 10^6$ K range, whereas active stars have large emission measures at $T = (1-2) \times 10^7$ K and likely hotter, although the energy sensitivity range of Einstein, ROSAT, and even ASCA make it difficult to infer much hotter temperatures if present. This difference in typical coronal temperatures between the active stars and the quiet Sun (but not the thermal phase of flares) is, I believe, critical to understanding the difference in radio emission properties.

As we have proceeded from optical to UV to X-ray emission, originating in progressively higher levels in the atmosphere and hotter plasmas, the solar-stellar connection is clear, but the differences between the quiet Sun and active stars are increasing rapidly. At centimeter wavelengths the solar-stellar connection itself may be lost. At 3.6 and 6 cm the quiet Sun radio luminosity is typically $L_{\rm R}^{\rm QS} \approx 10^{11}$ ergs cm^{-2} s^{-1} Hz^{-1}. The only other star with a measured luminosity even close to this level is the nearby (3.5 pc) star Procyon (F5 IV-V) with $L_{3.6} = 10^{11.7}$ ergs cm^{-2} s^{-1} Hz^{-1}. All other detected radio sources among the late-type stars and binary systems are far more radio luminous with $L_{\rm R}$ in the range $10^{13} - 10^{17}$ ergs cm^{-2} s^{-1} Hz^{-1}. Furthermore, these radio sources typically emit by the nonthermal gyrosynchrotron process, or in the case of K and M giants by thermal emission from their partially ionized winds. Neither of these emission processes is important for the Sun. It is appropriate to ask, therefore, whether there is indeed a solar-stellar connection at radio wavelengths.

An extremely important development in this field was the identification of a correlation between the thermal X-ray luminosity and the nonthermal cm-wave radio emission, $L_{\rm x} \approx 10^{15.5\pm0.5} L_{\rm R}$, valid over 6 orders of magnitude in both variables for all active late-type stars and solar flares. Güdel & Benz (1993) presented this correlation, although previous authors had proposed other relations for specific classes of stars like RS CVn binaries. Since the emission processes and electron distributions responsible for $L_{\rm x}$ and $L_{\rm R}$ are different, this apparently universal correlation is surprising, but it could reveal an important connection between the thermal and nonthermal electron reservoirs in active stellar coronae. I will explore this correlation further in Section 4.

For more detailed earlier reviews of the topic I call attention to the papers of Dulk (1985), Drake (1993), and Güdel (1994).

2. Radiation Mechanisms

It is useful to think in terms of a brightness temperature $T_{\rm B}$, the equivalent blackbody temperature for an optically thick radiating surface with radius R. The radio luminosity (erg s^{-1} Hz^{-1}) is then,

$$L_\lambda = 1.3 \times 10^6 \,(6{\rm cm}/\lambda)^2 \,(R_\star/R_\odot)^2 \left[(R/R_\star)^2\, T_{\rm B}\right]. \qquad (1)$$

2.1. Free-Free Emission from Chromospheres, Coronae, and Winds

Thermal free-free (FF) emission (also called bremsstrahlung) must always be present at some level from a partially ionized plasma, and will be the dominant emission process in the absence of relativistic electrons and magnetic fields. We can write the right-hand term in Eq. (1) as:

$$(R/R_\star)^2 T_\mathrm{B} = T_\mathrm{chr} + (1 - e^{-\tau})(R_\mathrm{cor}/R_\star)^2 T_\mathrm{cor} + (R_\mathrm{wind}/R_\star)^2 T_\mathrm{wind}, \quad (2)$$

where T_chr and T_wind are electron temperatures in the chromosphere and wind, respectively, at optical depths $\tau_\lambda = 1$. The first term, the contribution from the optically thick chromospheric layers, is typically in the range $(1-3) \times 10^4$ K for $\lambda = 6$ cm and increases to longer wavelengths. The contribution of the corona depends critically on the free-free optical depth,

$$\tau_\lambda^\mathrm{FF} = \frac{1 \times 10^{-21} L_\mathrm{x} \lambda^2}{T^{3/2} (R_\mathrm{cor}/R_\odot)^2}, \quad (3)$$

which is typically ≤ 1 for dwarfs and ≥ 1 for active giants. If we consider only free-free emission, then $L_\mathrm{x}/L_6 = 2.2 \times 10^{16}$ Hz, whereas the empirical relation (Güdel & Benz 1993) is $L_\mathrm{x}/L_6 = 3 \times 10^{15}$ Hz. Thus free-free coronal sources are radio weak. For optically thick thermal emission from a partially ionized wind with ionized mass loss rate $\dot{M}_\mathrm{ion}$, the flux density is,

$$S_\nu \sim \dot{M}_\mathrm{ion}^{4/3} v_\mathrm{wind}^{-4/3} D^{-2} \nu_5^{0.6} T_4^{0.1}, \quad (4)$$

where $\nu_5 = \nu/5$ GHz and $T_4 = T/10^4$. M giants and supergiants typically have optically thick winds.

It is instructive to consider some examples of free-free emission sources.

- For the quiet Sun, $\log L_6 = 11.0$ and $(R/R_\star)^2 T_\mathrm{B} = 8 \times 10^4$ K. Since $T_\mathrm{chr}(\tau_6 = 1) = 20,000$ K from models, coronal free-free emission dominates and the coronal optical depth is $\tau_\mathrm{cor} \approx 0.02$.

- Procyon provides a different result. Drake, Simon & Brown (1993) detected this nearby F5 IV-V star as a 33μJy source at 3.6 cm. This corresponds to $\log L_{3.6} = 11.7$ and $(R/R_\star)^2 T_\mathrm{B} = 3 \times 10^4$ K. Since from models $T_\mathrm{chr}(\tau_\lambda = 1) = 20,000$ K, the chromospheric emission dominates and $\tau_\mathrm{cor} \approx 0.003$, assuming that $T_\mathrm{cor} = 1.5 \times 10^6$ K and $R/R_\star = 1.5$.

- A third example is Capella (G8 III + G1 III), a long-period RS CVn binary, which Drake & Linsky (1986) detected as a 0.20 mJy source at 6 cm. This flux corresponds to $\log L_6 = 13.7$ and $(R/R_\star)^2 T_\mathrm{B} = 4 \times 10^6$ K. In this case the coronal emission dominates with $\tau_\mathrm{cor} \approx 0.7$, assuming that $T_\mathrm{cor} = 5 \times 10^6$ K and $R/R_\star = 2$.

- Last we consider the M3 III star μ Gem, which Drake & Linsky (1986) detected as a 0.18 mJy source. This flux corresponds to $\log L_6 = 14.7$ and $(R/R_\star)^2 T_\mathrm{B} = 6 \times 10^4$ K. Since the chromospheric contribution in Eq. (2) is $\leq 1 \times 10^4$, the wind emission dominates with $R_\mathrm{wind}/R_\star = 5 - 7$ for an assumed wind temperature in the range 1000–2000 K.

2.2. Gyroresonance Emission

When Gary & Linsky (1981) detected 6 cm emission from χ^1 Ori (G0 V) and UV Ceti (dM5.5e), they could not explain the observed fluxes by free-free emission. For example, the 0.60 mJy flux for χ^1 Ori corresponds to $\log L_6 = 14.0$ and $(R/R_\star)^2 T_B = 6.4 \times 10^7$ K. For a coronal temperature of 10^7 K, they found that the size of the corona is not unreasonably large, $R/R_\star = 2.5$, but the corona is optically thin, τ_6^{FF} (cor) = 0.13 and the radio flux is an order of magnitude smaller than predicted by Eq (2). To increase the coronal opacity with the same thermal electrons, they suggested that resonant absorption at low-order harmonics of the cyclotron frequency be included. For harmonics $s \leq 10$, the speeds of electrons in magnetic fields are nonrelativistic and the opacity is called "thermal gyroresonance" (GR) absorption. In their rough calculations they assumed that the coronal magnetic field diverges as in solar active regions, $B(r) = 0.25B_\circ(R/R_\star - 0.5)^2$, that the coronal temperature is 10^7 K, and that the photospheric magnetic field is 1000-2000 G. For these parameters $\tau_{GR} > 1$ for $R/R_\star \leq 1.65$, which comes close to explaining the observed flux.

Gyroresonance absorption does indeed provide additional coronal opacity, but even for hot coronae (say $T = 5 \times 10^7$ K), we expect that it can explain radio fluxes only when $(R/R_\star)^2 T_B \leq 2 \times 10^8$ K. Furthermore, gyroresonance emission decreases rapidly with increasing frequency and generally has low circular polarization. These properties limit its ability to explain cm-wave emission from solar active regions and UV Ceti at minimum flux (Güdel & Benz 1989). Higher luminosities require an emission process with significantly larger values of T_B.

2.3. Thermal Gyrosynchrotron Emission

It is a common approach in science to look for the simplest explanation for observables. Following this approach, Drake, Simon & Linsky (1989, 1992) considered whether the same thermal electrons in stellar coronae can explain both the observed X-ray and cm-wave radio emission. In particular, they attempted to explain the correlation between L_6 and L_x characterizing the low-level radio emission from RS CVn systems. Their approach differed from that just discussed in that they considered hotter electrons that have relativistic speeds in magnetic fields ($s \geq 10$). This emission process is refered to as "thermal gyrosynchrotron" (TGS) emission. For example, using radio VLBI techniques Mutel *et al.* (1985) found a core/halo structure in the UX Ari (K0 IV + G5 V) system outside of flares. For the halo component they found $T_B = 8 \times 10^8$ K and an emitting region size $L = 3 \times 10^{12}$ cm. One can explain the observed minimum 6 cm flux $S_\nu = 7.5$ mJy with $T = 5 \times 10^7$ K electrons (the hot component observed by the Einstein SSS instrument) with a coronal magnetic field of 200 G.

This explanation has two serious dificulties. First, 200 G magnetic fields located many stellar radii from an active star seem unlikely given that photospheric magnetic fields for these stars should be only about 1000 G and magnetic fields typically diverge at least as fast as a dipole. Second, beyond its peak the radio flux should depend on frequency as $S_\nu \sim \nu^{-8}$, whereas observations show a very slow decrease with increasing frequency (Chiuderi Drago & Klein 1990).

2.4. Nonthermal Gyrosynchrotron Emission

VLBI and now VLBA images of active stars and binary systems typically show emitting regions comparable in size to a stellar radius, moderate circular polarization, flat spectra in the cm range, slow time variability, and brightness temperatures in the range $10^8 - 10^{10}$ K. These properties characterize noncoherent gyrosynchrotron emission from a nonthermal distribution of electrons. During flares, however, M dwarfs show much higher brightness temperatures, high circular polarization, spectral structure, and rapid time variability, which characterize coherent emission processes.

Chiuderi Drago & Franciosini (1993) have made detailed calculations to determine whether the quiescent 6 cm emission of RS CVn systems is gyrosynchrotron emission from thermal and/or nonthermal electrons. In their calculations they assumed a magnetic field distribution $B \sim B_{\rm max} r^{-n}$, where $n =$ 1, 2, or 3, and a nonthermal electron energy distribution $N(\gamma) = K(\gamma - 1)^{-\delta}$, where the Lorenz factor γ characterizes the particle energy and δ is a constant. The nonflare cm-wave spectrum can be fit either with a thermal distribution of electrons and $n = 1$ (which is unrealistic), or a nonthermal distribution of electrons with $B = 10$ G and $\delta = 1.58$. They also found that a flare model with $B_\circ = 1000$ G in a compact loop and $\delta = 2 - 3$ decays by synchrotron radiation and collisions in 7 days to low level (i.e., quiescent) emission from an extended area with $B = 10$ G. Mutel *et al.* (1985) arrived at a similar conclusion.

Examples of nonthermal gyrosynchrotron (NGS) emission sources include the magnetic chemically peculiar stars, F-M main sequence stars, weak-lined T Tauri stars, and active binary systems including the RS CVn, Algol, and W UMa systems. Summaries of these observations can be found elsewhere in these Proceedings. Two detailed models proposed to explain nonthermal gyrosynchrotron emission are the RS CVn model of Morris, Mutel & Su (1990), but see Storey (1995), and the wind-driven magnetosphere model that Linsky, Drake & Bastian (1992) proposed for magnetic chemically peculiar stars. Table 1 summarizes the parameter ranges for which each emission process can be important. The parameters are for 3.6 cm radiation assuming that $R_\star/R_\odot = 1$. $< E >$ is the mean energy of the radiating electrons and d is the farthest distance that a star with luminosity $L_{3.6}$ can be observed with the VLA.

3. Understanding the $L_{\rm x} - L_{\rm R}$ Relation

The surprising relation of the X-ray and radio emission that appears to be valid for all active late-type stars and binary systems over at least 6 orders of magnitude in both variables could be easily understood if the emission processes of the X-ray and radio emission were either both thermal or both nonthermal, but this is unlikely the case. One motivation for our attempting to explain stellar radio emission as either thermal gyroresonance emission (Gary & Linsky 1981) or thermal gyrosynchrotron emission (Drake, Simon & Linsky 1992) was to show that the radio and X-ray emission could be due to the same electrons. Since such attempts have proven to be unacceptable, we must conclude that there is a statistical relation between the nonthermal and thermal electrons and we must search for its physical origin. The alternative of assuming some sort of exotic physics is personally unacceptable.

Table 1. Parameter ranges for each emission process.

$\log L_{3.6}$	d (pc)	$(R/R_\star)^2 T_{\rm B}$ (K)	$< E > (R_\star/R)^2$	FF	GR	TGS	NGS
11	1.6	2.5×10^4	2 eV	X			
12	5	2.5×10^5	20 eV	X			
13	16	2.5×10^6	200 eV		X		
14	50	2.5×10^7	2 keV		X		
15	160	2.5×10^8	20 keV		X	X	X
16	500	2.5×10^9	200 keV			X	X
17	1600	2.5×10^{10}	2 MeV				X
18	5000	2.5×10^{11}	20 MeV				X

I will propose a schematic model in the hope that theoreticians will develop it further. In my model I assume that the thermal and nonthermal electrons coexist in the same volume in a quasi statistical steady state. Thus there is a continual exchange between the reservoirs of thermal and nonthermal electrons by acceleration and thermalization processes (primarily collisions at lower energies and gyrosynchrotron radiation at higher energies). These processes lead to a quasi steady state, averaged over space and time, although at any one location and time acceleration or thermalization may dominate. This model is fundamentally different from the dynamical model of Chiuderi Drago & Franciosini (1993) in which the quiescent emission is due to post-flare electrons that have expanded from the flare site into an extended volume with low magnetic field strength during a seven-day period. I refer to my model as the "peaceful co-existence" model to emphasize its continuous nature.

Consider a Maxwell-Boltzmann distribution of electrons in a statistically varying electric field $E(t)$ produced by the time-varying magnetic fields. These electrons will see an acceleration force $F_{\rm accel} = eE(t)$ and a drag force through the thermal plasma, $F_{\rm drag} \sim (n_e/T)(v_{\rm th}/v)^2$, where I have considered speeds that exceed the thermal speed, $v \gg v_{\rm th} = \sqrt{kT/m}$. These electrons will be accelerated when $F_{\rm accel} > F_{\rm drag}$, which occurs when the electron speed exceeds a critical value $v > v_{\rm c} \sim \sqrt{n_e/E}$. Such electrons will become nonthermal as increasing speed means lower drag and gyrosynchrotron radiation is unimportant until the electrons become nearly relativistic. This continuous acceleration process when $v > v_{\rm c}$ is often described as "runaway." All electrons exceeding the thermal speed are accelerated when electric fields exceed the Dreicer field,

$$E > E_{\rm D} = \frac{4\pi e^3 n_e \ln \Lambda}{kT}. \quad (5)$$

When this occurs during a flare, the nonthermal reservoir is highly populated. Here I consider electric fields that are only strong enough to accelerate the high energy tail of the distribution in what could be called the "sub-Dreicer" regime. For a more detailed description of this process see, for example, Holman (1985, 1995) and Norman & Smith (1978).

A rough estimate of the ratio of nonthermal to thermal electrons in the sub-Dreicer regime is:

$$\frac{N_{\rm nonth}}{N_{\rm th}} \approx \int_{v_c}^{\infty} f(v)dv \Big/ \int_{0}^{\infty} f(v)dv. \tag{6}$$

This equation is only approximate because collisions are required to establish the Maxwell-Boltzmann tail, which is being accelerated. Rough estimates of $N_{\rm nonth}/N_{\rm th}$ in the coronae of active stars (e.g., Morris et al. 1990, Chiuderi Drago & Franciosini 1993) place this ratio at 10^{-6} to 10^{-7}. This corresponds to $v_c/v_{\rm th}$ = 3.5 to 4.0, or the energy ratio $e_c/e_{\rm th} \approx 12$ to 16. ROSAT and ASCA observations show that active late-type stars typically have peak coronal emission measures at $\sim 10^7$ K, corresponding to $e_{\rm th} \approx 1$ keV. Thus for these stars the nonthermal regime should begin at ≥ 10 keV. X-ray observations in this energy range, which is just beyond the energy range of ASCA, AXAF, and XMM, would be an important test of this prediction. The X-ray Timing Explorer (XTE) satellite to be launched in 1995 may provide the first clear test.

A natural explanation for why the Sun is not usually a gyrosynchrotron radio source is that the solar corona has very little plasma hotter than 2×10^6 K. If e_c is the same as for the active stars, then $e_c/e_{\rm th} \approx 12/0.2 \approx 60$. Extremely few solar coronal electrons have the required energy to enter the acceleration regime. Should $e_c \approx E/n_e$ be similar in the coronae of the Sun and active stars? There is as yet no good theory for this, but empirically active (but not flaring) stellar coronae have high densities and high heating rates. This suggests that $e_c \approx E/n_e$ may be similar for the nonflaring Sun and the active coronal stars.

4. Summary

In this short review of low-level stellar radio emission, I have emphasized the present absence of a solar-stellar connection at radio wavelengths and the challenges for establishing such a connection on both observational and physical grounds. As new observing capabilities emerge in this strongly data-driven field, I encourage researchers to keep in mind the following points:

- Observations of stellar radio emission analogous to what is observed on the quiet Sun is for the present severely limited by the short observing horizon even for long duration observations with very sensitive instruments like the VLA. Nevertheless, very deep observations of nearby inactive stars, even though predicted flux levels may be near or somewhat below threshold, are needed to establish or reject the hypothesis that the quiet Sun-stellar connection at radio wavelengths is indeed real.

- Radio emission from most detected late-type stars and active binary systems is typically ascribed to gyrosynchrotron emission from mildly relativistic electrons, except for large flaring events on dMe stars. However, nonthermal gyrosynchrotron emission is not observed in the quiet Sun and is not the predominant flare emission process on the Sun at cm wavelengths. The fundamental difference between the Sun and the detected radio stars is likely due to the solar corona, unlike active stellar coronae, not having much plasma at or above 10^7 K.

- The observed correlation between thermal X-ray emission and nonthermal radio emission, $L_x \sim 10^{15.5\pm0.5} L_R$, which appears to be valid for all types of active late-type stars, indicates a close relation between the reservoir of thermal and nonthermal electrons in stellar coronae. The physical explanation for this coupling provides a major challenge for stellar radio astronomy. Is the coupling between the two reservoirs dynamic, as proposed in post-flare and nonequilibrium models for quiescent radio emission, or is it quasi-static, with hot electrons in the Maxwell-Boltzmann tail continuously running away due to electric fields in the sub-Dreicer regime?

- Since the heating and particle acceleration processes are likely two aspects of the same process, in my opinion, a successful theory of heating and particle acceleration will naturally explain the $L_x \sim L_R$ relation.

- A missing observed quantity is hard X-ray emission from the nonthermal electrons responsible for the observed nonthermal gyrosynchrotron emission. While sensitivity thresholds make it very unlikely in the near future to observe stellar 100 keV – 1 MeV X-ray emission even during giant flares, it may be feasible with the new XTE satellite to detect 10–20 keV X-ray emission, which is likely the beginning of the nonthermal electron distribution. Such observations should be attempted and could provide an important constraint on quasi-static theories of particle acceleration.

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