The Radio–X-ray Relation in Cool Stars: Are we headed toward a divorce?

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Abstract. This splinter session was devoted to reviewing our current knowledge of correlated X-ray and radio emission from cool stars in order to prepare for new large radio observatories such as the EVLA. A key interest was to discuss why the X-ray and radio luminosities of some cool stars are in clear breach of a correlation that holds for other active stars, the so-called Güdel-Benz relation. This article summarizes the contributions whereas the actual presentations can be accessed on the splinter website.1

1. Radio emission and X-rays as diagnostics of coronal energy release

X-rays and radio emission are excellent diagnostic probes to study energy release in magnetized stellar coronae. Solar observations have been key to deciphering the plethora of phenomena seen in these wavelength ranges. In brief, X-rays trace the presence of dense, hot (million-degree) plasma trapped in closed coronal magnetic fields, heated by processes that are still not fully understood. Radio observations, in contrast, probe both thermal atmospheric components from the chromosphere to the corona, and populations of non-thermal, accelerated electrons, typically residing in low-density, open or closed coronal magnetic fields.

A solar-stellar analogy is, however, complicated by phenomenology in magnetically active stars that is, at first sight, not present in the Sun. X-ray emission becomes much stronger toward more active stars, most likely as a result of increased surface coverage with active regions; however, the average, “characteristic” temperature of the corona increases along with the coronal luminosity (e.g., Schrijver et al. 1984; Güdel et al. 1997), a trend that requires additional physical explanation. At radio wavelengths, magnetically active stars also show a different face. Solar radio emission in the

1http://cxc.harvard.edu/cs16xrayradio/
1-10 GHz range is dominated by bremsstrahlung from various chromospheric/transition region levels and by optically thick gyroresonance emission from coronal layers above magnetic active regions. In contrast, observed radio brightness temperatures and radio spectra from active stars indicate gyrosynchrotron radiation from electrons with much higher energies than typically present in the solar atmosphere. The Sun occasionally features gyrosynchrotron emission, often accompanied by a variety of coherent radiation types (see Sect. 2), but such radiation is confined to episodes of flaring.

Magnetically active stars reveal further radio properties lacking any clear solar analogy such as extremely large coronal structures with size scales of order a stellar radius and more (e.g., Benz et al. 1998; Mutel et al. 1998; Peterson et al. 2010). In contrast, X-ray coronae tend to be rather compact even in extremely active stars (e.g., Walter et al. 1983; Ottmann et al. 1993): this is a consequence of the X-ray brightness scaling with the square of the electron density combined with relatively small pressure scale heights. Radio and X-ray sources are therefore not necessarily co-spatial and probe rather different plasmas or particle populations in stellar atmospheres, different atmospheric layers and structures, and perhaps even different energy sources. There should be little reason to expect that the two types of radiation are correlated in stars.

It therefore came as a surprise when such a correlation was uncovered for the steady radio and X-ray luminosities of RS CVn close binary stars. Drake et al. (1989) found that the soft X-ray and radio (6 cm) luminosities are correlated over a few orders of magnitude albeit somewhat different from a linear trend \( L_R \propto L_X^{1.37 \pm 0.13} \). They
suggested a self-consistent scheme in which the radio emission originates from the
tail of the Maxwellian electron distribution of a very hot (>50 MK) plasma through
the gyrosynchrotron process; such a plasma component is suggested from X-ray ob-
servations. This model is elegant as it links X-rays and radio emission by suggest-
ing a common source. However, serious difficulties remain. Gyrosynchrotron spectra
from a thermal plasma reveal a steep decline toward higher frequencies not observed in
any magnetically active star; an acceptable spectral fit requires an extraordinary setup
of the coronal magnetic field, such as a field strength decreasing with radius as $r^{-1}$
(Chiuderi Drago & Franciosini 1993; Beasley & Güdel 2000). Non-thermal (power-
law) electron distributions, in contrast, readily produce shallow spectra as observed, es-
pecially if the “aging” of an injected electron distribution, leading to spectral modifica-
tions due to synchrotron and collisional losses, is taken into account (Chiuderi Drago & Franciosini
1993).

A closer inspection of stars more akin to the Sun is in order. To that end, Güdel et al
(1993) studied X-ray and radio luminosities for M dwarfs, followed by other spectral
types including G dwarfs (e.g., Benz & Güdel 1994; Güdel et al. 1995). Again, active
stars of all late-type spectral classes followed a similar trend, best described by a pro-
portionality, $L_X/L_R \approx 10^{15.5 \pm 0.5}$ Hz (in the following referred to as the GB relation).
Combining these samples with samples of RS CVn binaries, Algol binaries, FK Com-
type stars and also pre-main sequence weak-lined T Tauri stars, a coherent trend is
found over 5-6 orders of magnitude in $L_R$ and $L_X$ (Figure 1). It is important to note
that the $L_X/L_R$ ratio is by no means universal. It has been demonstrated exclusively for
magnetically active stars but does clearly not apply to inactive stars like the Sun; such
stars keep appreciable levels of quasi-steady soft X-ray emission but are not sources
of continuous radio emission of the gyrosynchrotron type. In fact, present-day radio
observatories still cannot systematically detect nearby cool stars except for extremely
active examples.

Active stars stand out by two properties mentioned above - their extremely hot
plasma seen in X-rays, and their non-thermal electron populations evidenced by their
radio emission. Let us assume that the energy initially contained in the accelerated
electrons eventually heats the coronal plasma. If the corona releases energy at a rate $\dot{E}$
by injecting accelerated electrons at an energy-dependent rate $\dot{n}_\text{in}(\epsilon)$, then

$$\dot{E} = \frac{1}{a} \int_{\epsilon_0}^{\infty} \dot{n}_\text{in}(\epsilon) \epsilon d\epsilon = \frac{1}{b} L_X$$

(1)

where $a$ is the fraction of the total energy that is channeled into particle acceleration
and $b$ is the fraction of the total energy that is eventually radiated as soft X-rays. Eq. [1]
assumes an equilibrium between energy injection and energy loss. After introducing
radiation processes into Eq. [1] one finds (Güdel & Benz 1993)

$$L_R = 3 \times 10^{-22} B^{2.48} \frac{a}{b} \tau_0 (\alpha + 1) L_X$$

(2)

i.e., a proportionality if several parameters on the right-hand side take characteristic,
constant values, in particular $B$ and the ratio $a/b$ ($\alpha$ is the power-law index for the
energy dependence of the electron lifetime). Conversely, comparing Eq. [2] with observ-
ations, one finds (e.g., for $a/b \approx 1$) the time scale $\tau_0$ for electron trapping (i.e., the
lifetime of the population), concluding that the radiation must decay on time scales of
minutes to hours in most cases. This necessitates frequent or quasi-continuous replen-
ishment of the corona by high-energy electrons.
This mechanism is what the “standard model” for a solar flare would predict. The standard solar flare model, the chromospheric evaporation scenario, posits that electrons initially accelerated in reconnecting magnetic fields propagate to chromospheric layers where they heat and ablate material which escapes into closed magnetic loops and cools by X-ray radiation. The best observational evidence for this model is the “Neupert Effect”, stating that the time derivative of the flare X-ray light curve resembles the radio (or hard X-ray or U-band) light curve, \( dL_X/dt \propto L_R \).

This prediction follows from assuming that \( L_X \) roughly scales with the thermal energy content in the hot plasma accumulated from the high-energy electrons, while radio emission scales with the number of such electrons present at any given time. The Neupert Effect is frequently observed in solar flares (e.g., Dennis & Zarro 1993), but has also frequently been seen in stellar flares, both extremely large events and the smallest yet discerned in stellar X-rays (e.g., Güdel et al. 1996, 2002; Osten et al. 2004).

We need one further ingredient, relating flares to the observed quiescent emission. During the past decade, a number of studies have shown that the occurrence rate of stellar flares in X-rays is distributed as a power law in radiated energy (a concept familiar to solar physics), \( dN/dE \propto E^{-\alpha} \), with \( \alpha \approx 2 \) (e.g., Audard et al. 2000; Kashyap et al. 2002). In that case, and assuming that the power law continues toward smaller energies, the energy integration, \( \int_{E_0}^{\infty} E(dN/dE)dE \) diverges for \( E_0 \to 0 \), i.e., a lower cut-off is required. More relevant here, the entire apparently steady emission level could be explained by the large number of small flares that superpose to a quasi-steady emission level while not recognizable individually in light curves.

Assembling the above pieces, we then suggest to solve the \( L_X - L_R \) puzzle as follows: Radio and X-ray emission correlate in magnetically active stars because the radiation we perceive as “quiescent” emission is made up of contributions from numerous small flares; each of these flares heats plasma by transforming kinetic energy from accelerated electrons; a portion of the latter is evident from their radio emission, while the heated plasma is observed by its X-ray emission. The \( L_X/L_R \) ratio therefore reflects the energy loss ratio of individual flares. As a check, we consider whether solar and stellar flares reveal radiative output ratios similar to those of the “quiescent” radiation. Average X-ray and radio luminosities for a range of solar flares (with specified total flare durations) as well as a sample of stellar flares are overplotted in Fig. 1. Indeed, the solar flares continue the trend seen in magnetically active stars (Benz & Güdel 1994) and the stellar flares show luminosity ratios in perfect agreement with the trend for quiescent emission. These observations support a picture in which flares are at the origin of coronal heating, of the steady radiation in magnetically active stars, and consequently of the \( L_X/L_R \) correlation.

2. The Sun

Correlation of Solar and Stellar X-rays with Gyrosynchrotron Radio Emission. X-ray emission from stellar and solar flares and coronae is produced by bound-bound transitions and by bremsstrahlung of rapidly moving electrons deflected on ions. The emission comes in two flavors depending on the energy distribution of the electrons: thermal or non-thermal. Thermal X-rays range from less than 0.1 keV to more than 10 keV, resulting from temperatures in the range between \( 10^6-8 \) K. Non-thermal X-rays are emitted by energetic electrons, accelerated by plasma processes. Their bremsstrahlung emission is observed in solar flares from about 10 keV up to 100 MeV. It is approximately a power law in the photon energy spectrum, often with some breaks caused by
a change in power-law index. The observed spectrum indicates a power law also in the
energy distribution of electrons.

Gyrosynchrotron radio emission is produced by individual particles, usually mildly
relativistic (> 100 keV) non-thermal electrons. The emission is caused by their spiral-
ing motion in magnetic fields (e.g., Dulk & Marsh 1982). Each high-energy electron
radiates both bremsstrahlung and gyrosynchrotron emission. Although different param-
eters enter the emissivity (most notably the magnetic field in the gyrosynchrotron case),
it is not surprising that non-thermal X-rays and gyrosynchrotron emission correlate in
solar flares. Kosugi et al. (1988) find a linear correlation between non-thermal X-ray
and radio peak fluxes with deviations of less than a half order of magnitude. It is more
surprising that in both stellar quiescent and flaring coronae, the thermal (soft) X-ray
luminosity also correlates with gyrosynchrotron radio emission (see above).

The correlation of non-thermal gyrosynchrotron radiation and thermal X-ray emis-
sion fits the standard flare scenario of flares: A significant fraction of the flare energy
is released in the form of non-thermal electrons, which precipitate to a dense medium
and heat it to the point of thermal X-ray emission. The scenario has not been con-
firmed in solar flares at a quantitative level. It is surprising, nevertheless, that over the
large range and widely different objects the correlation remains within half an order of
magnitude (Krucker & Benz 2000). In particular, the magnetic field and electron life
time are expected to change. Some deviations are noted: RS CVn binaries, Algols, and
BY Dra binaries tend to be radio-rich (Güdel & Benz 1993), nanoflares are radio-poor
(Krucker & Benz 2000). These differences may be the result of different parameters in
Eq. (2).

The excellent correlation of the radio/X-ray relation has several consequences:
1) The identical relation for flares and active star quiescent X-ray emission strongly
suggests that their X-ray emitting corona is flare heated.
2) The radio/X-ray relation has allowed the discovery of radio emission of K, G, and
F stars. Selecting bright X-ray emitters among these stellar types, they were easily
detected for the first time in radio emission (Güdel et al. 1994; Güdel 2002).
3) A large deviation from the relation can be used to identify radio emission originating
by a mechanism other than gyrosynchrotron (e.g., Benz 2001).

Correlation of Solar Soft X-rays with Coherent Radio Emission. Cosmic radio
emission originates in two ways: coherent and incoherent. Gyrosynchrotron and ther-
mal radiation are incoherent and result from the emission of individual particles. Con-
versely, coherent emission is produced by a group of particles emitting in phase. The
phasing may be caused by a wave in the plasma driven by an instability. Such insta-
bilites occur in plasmas where electrons have non-thermal velocity distributions, such
as a beam component, a loss-cone or strong electric current (Benz 2002). In wave
terminology, the plasma wave is transformed into radio waves (Melrose 1980). Ex-
citation and transformation are highly non-linear. Thus the correlation with X-rays is
weak or absent. Characteristics of coherent radio emission are a narrowband spectrum
(Δν/ν ≪ 1), high polarization ( ≥ 40% ), and extremely high brightness tempera-
ture ( ≥ 10¹⁰ K). An example of various coherent emissions is shown in Fig 2. At
frequencies above 3000 MHz, gyrosynchrotron radiation appears as diffuse broadband
structures increasing to higher frequencies beyond the instrumental limit at 4000 MHz.

Coherent radio emissions from the Sun have been reported at all wavelengths
longer than 3 cm. At meter wavelengths, they are classified as the well-known Type
I to V of radio bursts. At shorter wavelength, the metric types gradually disappear ex-
Figure 2. Spectrogram of solar flare radio emission in meter and decimeter waves observed with Phoenix-2 at ETH Zurich. The frequency increases downward. The example shows a clear separation of incoherent gyrosynchrotron emission at high frequencies and various coherent emissions at low frequencies.

ccept Type III bursts which have been identified at up to 8.5 GHz. Other types, classified as DCIM, dominate at decimeter wavelengths. They consist of broadband pulsations, patches of continuum or narrowband spikes. Figure 5 in Benz (2009) displays the highest fluxes reported. Gyrosynchrotron emission (marked therein as IV) dominates up to 10 cm, followed by DCIM emission possibly directly associated with flare energy release, and Type II emission caused by coronal shock waves dominating above 100 cm. We note that a flux density of $10^6$ solar flux units (sfu) at 1 AU corresponds to 100 μJy at 50 pc.

Solar coherent radio emissions were extensively compared to X-ray observations by the RHESSI and GOES satellites in a survey by Benz et al. (2005). The survey finds that 17% of the X-ray flares larger than GOES class C5 are not associated with coherent radio emission between 0.1 and 4 GHz. A later study, however, showed that all of the “radio-quiet” flares occurred either near the limb or showed emission below 0.1 GHz (Benz et al. 2007). Thus all flares appear to be associated by coherent radio emission.

Figure 2 shows that gyrosynchrotron emission may be associated with coherent radio emission but not correlate in detail. Correlation has been investigated not with gyrosynchrotron emission, but non-thermal X-rays which can be taken as a proxy. Some cases with good temporal correlation have been reported by Dabrowski & Benz (2009). However, recent imaging observations show that even correlating coherent radio emission does not originate from the location of coronal X-ray emission where electron acceleration is expected (Benz, Battaglia & Vilmer, in prep.). The current interpretation of coherent radio emission still associates some of the DCIM emissions with particle acceleration, but not necessarily with the major acceleration site. The new imaging
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Figure 3. X-ray vs. radio luminosity for different simultaneous multi-wavelength observations of 5 different active stars: two Algol systems (Algol, HR 5110), two RS CVn binary systems (HR 1099 and UX Ari), and one BY Dra binary system (CC Eri). The dotted lines indicate the $L_X/L_R = \kappa \times 10^{15.5 \pm 0.5}$ Hz ($\kappa=0.17$) relationship in Benz & Güdel (1994). The dashed line gives the average $L_X/L_R = 5.9 \times 10^{14}$ Hz from these data, and the solid line shows the GB relation with $\kappa=1, L_X/L_R = 10^{15.5}$ Hz.

observations therefore require a flare model that has a much larger volume than the coronal X-ray sources currently observable.

Coherent radio emissions from solar flares do not correlate with thermal X-rays in detail except for the "big flare syndrome" (larger flares being generally more luminous at all wavelengths). Benz et al. (2006) find that the total energy emitted in decimeter radio waves scales on the average with the peak soft X-ray flux as $E_{\text{radio}} = 1.92 \times 10^8 F_{\text{SXR}}^{1.42}$ [erg] where $E_{\text{radio}}$ is in units of $10^{20}$ erg and $F_{\text{SXR}}$ is the GOES flux from 1.8 to 12.4 keV in units of W/m$^2$. The correlation coefficient is 0.75, with a 95% significance range between 0.34 and 0.92. The scatter is more than an order of magnitude.

In most active stars and planets where the plasma frequency, $\omega_p$, exceeds the electron gyrofrequency $\Omega_e$, coherent radio emission is dominated by gyromagnetic maser emission at the first harmonic $\nu = \Omega_e/2\pi = 2.80 \times 10^6 B$ [Hz]. Thus coherent radio emission, although not a measure for flare importance, may be used to measure the magnetic field strength in stellar and planetary atmospheres.

3. RS CVn, Algol, and BY Dra Systems

Active binaries consisting of RS CVn, BY Dra, and Algol systems all lie at the upper right corner of the $L_X$ vs. $L_R$ diagram (Fig. 3), exhibiting the extremes of magnetic activity. However, these objects are also known to be highly time-variable sources. This gives pause to whether relationships connecting time-averaged behaviors hold when strictly simultaneous observations are used.
Based on simultaneous data summarized in the caption, Figure 3 shows the radio-X-ray correlation for five objects in comparison to the GB relation. Radio and X-ray variability are apparent, but most of the time these hyperactive stars do display $L_X$ and $L_R$ values which are consistent with the GB relation, albeit with a fair amount of scatter. Note, however that the range of variability differs between the two. For HR 1099 alone, $L_R$ spans a range of 230 while only spanning a factor of 6 in $L_X$.

The conventional explanation for the nearly linear relationship between the two luminosities argues that there is a common energy reservoir out of which both plasma heating and particle acceleration occur, and these processes occur at a roughly fixed ratio between different classes of active stars. In the current situation, however, we can see that while this may be true in a time-averaged sense, the examples of uncorrelated radio and X-ray flaring which produce the extreme values of $L_X/L_R$ have different ratios of particle acceleration and plasma heating. This is also true for flares which exhibit the Neupert effect (the green light curve of CC Eri contains one such example), where the instantaneous $L_X/L_R$ ratio varies by a factor of 20 during the initial stages of the flare, spanning preflare conditions to the time when the flare-associated particle acceleration is occurring (radio luminosity peak) to the maximum flare-associated plasma heating (peak of the X-ray luminosity).

### 4. Young Stellar Objects

High-energy processes in Young Stellar Objects (YSOs) as observed in both the radio and the X-ray wavelength regime have been known for some time (e.g., Feigelson & Montmerle 1999). Very early evolutionary stages of YSOs, class I protostars, emit strong X-ray emission and nonthermal radio emission, presumably both due in large part to magnetically induced flares. However, it is still unclear in which stage YSOs become radio-active. Since most YSOs are relatively weak radio continuum sources, an observational difficulty has been to unambiguously find genuine nonthermal radio sources, e.g., by their polarization. YSOs can also produce free-free thermal radio emission in ionized material, for example at the base of outflows or jets (for a review of YSOs in the context of stellar radio astronomy, see Güdel et al. 2002).

Over the last decade, YSO X-ray variability research has been put on a much improved statistical basis, particularly for short timescales. However, centimetric radio variability on similar scales has only been studied toward a few sources (e.g., Forbrich et al. 2008). The correlation of variability in both wavelength ranges as well as the overall correlation of time-averaged radio and X-ray luminosities, as could be expected if the GB relation applies, remains unclear. While necessary to eliminate the effects of variability, there have only been a few simultaneous radio and X-ray observations.

Feigelson et al. (1994) obtained the first simultaneous radio and X-ray observations of a T Tauri star, targeting V773 Tau. They found uncorrelated variability, suggesting that the two emission mechanisms are decoupled. Following the discovery of the first class I protostar with nonthermal radio emission (Feigelson et al. 1998), the question of when protostars begin to be radio-active became more acute. Gagné et al. (2004) carried out a simultaneous radio and X-ray observing campaign of ρ Oph, a region rich in YSOs of all classes. They detected several T Tauri stars in both wavelength ranges. The first simultaneous X-ray and radio detections of class I protostars were reported by Forbrich et al. (2007) (see also Forbrich et al. 2006), targeting the Coronet cluster in CrA. With observations of the LkHα101 cluster, Osten & Wolk (2005) for
the first time used simultaneous X-ray and multi-frequency radio observations to show that some sources show an inverse correlation between radio flux and spectral index. Most recently, observations of IC 348 and NGC 1333 have been carried out, but only few YSOS are detected in both bands (Forbrich, Osten, & Wolk, submitted).

All these simultaneous measurements agree on the location of YSOs on an $L_X$ vs. $L_R$ plot. Both luminosities are among the highest observed toward stars. YSOs do not seem to fall directly on the GB relation, but they are shifted toward higher radio luminosities for a given X-ray luminosity. Still, there are only a few YSOs that seem to be clearly off the GB relation and their numbers are too low to provide firm conclusions. To date observations have been limited by the radio sensitivity, but the Expanded Very Large Array will soon lead to far more radio detections among YSOs. Higher signal-to-noise ratios will also allow us to better distinguish non-thermal (e.g., gyrosynchrotron) and thermal radio sources. Interesting insights are also coming from VLBI radio observations (e.g., Dzib et al. 2010).

5. The X-ray-Radio Disconnect in Ultracool Dwarfs

Prior to the first detection of radio emission from an ultracool dwarf (Berger et al. 2001), measuring radio emission from very low mass stars and brown dwarfs seemed improbable. Given the tight correlation between radio and X-ray emission in higher-mass, coronally-active stars, initial X-ray results predicted radio emission well below detectable limits. The detection of a radio flare from LP944-20 required a severe violation of the GB relation, with $L_{\nu,\text{rad}}/L_X \gtrsim 10^{-11.5}$ Hz$^{-1}$. Subsequent radio detections of ultracool dwarfs (Berger 2002) have yielded similar results, indicating a general violation of the correlation in this regime.

With a large sample of simultaneous observations, Berger et al. (2010) conclusively demonstrated this correlation no longer holds for objects beyond spectral type M6. For M dwarfs in the range M0-M6, the ratio of radio to X-ray emission is $L_{\nu,\text{rad}}/L_X \approx 10^{-15.5}$. This ratio steadily increases for cooler objects. In the range M7-M8 it is around $10^{-14}$ and beyond M9 it is greater than $10^{-12}$. It should be noted that there are a few objects which have been detected in the X-rays without corresponding radio emission, and hence may not violate the correlation. However, with the exception of a marginal detection from the L dwarf Kelu-1, these are all earlier objects in the range M7-M9 and most do not have deep radio luminosity limits and may yet be detected.

To investigate the nature of the breakdown of X-ray/radio correlation, it useful to examine the trends of the X-ray and radio emission in ultracool dwarfs separately. Berger et al. (2010) showed a sharp decline in X-ray activity for objects with spectral types beyond M7. In contrast, they also found indications for an increase in the ratio activity ($L_{\text{rad}}/L_{\text{bol}}$) for those objects cooler than M7. It is clear, then, that the breakdown is the due to the decline in X-ray luminosity combined with the sustained strength of the radio emission. But why do particle acceleration and plasma heating no longer correlate? As demonstrated by the radio emission, neither magnetic field dissipation nor particle acceleration appear to be affected by the increasingly neutral atmospheres of ultracool dwarfs. The total radio luminosities remain roughly constant even in these cooler objects, indicating the fraction of magnetic energy that goes into accelerating the electrons responsible for the radio-emission does not change, nor does the efficiency of field dissipation.

The difference appears to lie in the efficiency of the plasma heating, which is responsible for the hot X-ray producing gas. If the radio-emitting electrons are directly
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responsible for plasma heating in higher mass stars, the enhanced trapping of these
electrons could account for the breakdown in the correlation. It could also be pro-
duced by a change in the geometry of the radio-emitting regions, should they evolve to
smaller sizes in lower-mass objects and hence have less of an effect on the large-scale
coronal heating. However, this is unlikely given that rotationally stable, quiescent radio
emission and periodic H\(\alpha\) emission has been detected from several ultracool dwarfs,
indicative of large magnetic filling factors.

Since radio emission requires only a small population of relativistic electrons, a
decline in the bulk coronal density could suppress the X-ray heating without affecting
the radio emission. The decreased X-ray emission, if caused by a loss in coronal den-
sity, could be attributed to coronal stripping. There are hints of super-saturation in the
X-ray-rotation relation in the fastest rotators among the ultracool dwarfs (Berger et al.
2008). For objects later than M7, there is decline in \(L_X/L_{bol}\) for objects with decreasing
rotation periods. The median value of \(L_X/L_{bol}\) is \(\approx 10^{-4}\) for \(P > 0.3\) d, while for
\(P < 0.3\) d it is \(L_X/L_{bol} \approx 10^{-5}\). The combination of rapid rotation and the shrinking co-
rotation radius in lower mass stars may lead to the decrease in X-ray emission among
these objects. In comparision, there are indications that the fastest rotators among ultra-
cool dwarfs are more likely to be detected in the radio and are the most severe violaters
of the X-ray-radio correlation (Berger et al. 2008).

In contrast to hotter stars which primarily produce radio emission through gy-
rosynchrotron radiation, several ultracool dwarfs have been observed with short-duration,
highly polarized, narrow band, bursts which can be attributed to a coherent emission
process, such as the electron cyclotron maser (ECM) instability (Benz 2001; Hallinan et al.
2007, 2008; Berger et al. 2009). Although this process cannot account for all radio
emission detected from ultracool dwarfs, this change in emission mechanism may be
indicative of a change in the properties of the relativistic electron population and its
impact on large-scale coronal heating.

6. Conclusions

In short, we are not headed toward a divorce. Instead, the X-ray and radio luminosities
of cool stars appear to be in an “open relationship” where a lot depends on the type of
radio emission that is present. Until now, observational data have not always been sen-
tive enough to unambiguously identify dominant emission mechanisms, for example
in the case of YSOs. Clearly, the \(L_X/L_R\) relation does not apply to all stars. As men-
tioned above, inactive stars violate this relation as they do not show non-thermal radio
(gyrosynchrotron) emission. The “non-flaring” Sun is an example. Either, there are
additional heating mechanisms at work in these stars that do not involve high-energy
electrons, or the energy transformation process is more efficient in heating the plasma
to sufficiently high temperatures so as to become visible in X-rays. The other impor-
tant class of stars violating the relation are brown dwarfs, but coherent radio radiation
mechanisms may matter here. Similarly, a number of protostellar objects do not follow
the standard trend although they are magnetospheric radio and X-ray sources. Here,
however, the measurement of either of the luminosities is difficult. Radio gyrosyn-
chrotron emission may be attenuated by overlying ionized winds (e.g., the jets easily
detected as thermal radio sources); X-ray emission could be partially attenuated by
neutral gas masses, such as neutral winds, accretion streams, or molecular outflows. If
only part of the coronal emission is (fully) attenuated, e.g., by accretion streams, then
an assessment of the intrinsic luminosities becomes impossible. Further observations,
particularly deeper radio observations with new instruments such as EVLA, as well as large X-ray surveys with Chandra and XMM-Newton will help shed light on the limits of the radio/X-ray correlation in cool stars.

Appendix: What is the connection between nonthermal radio emission and thermal X-ray emission?

The lack of consensus among the theoreticians concerning which physical models best explain heating and particle acceleration and the GB correlation suggest to Jeff Linsky that there must be a simple approach to understanding the relevant physics. Given that flares occur when there are rapid changes in the structure of complex magnetic fields, Maxwell’s equations require the presence of electric fields and currents. In a plasma the acceleration force of the electric field \( F_{\text{accel}} = eE \) is opposed by a collisional drag force \( F_{\text{drag}} \approx (n_e/T)(v_{th}/v)^2 \) when the speed \( v \) exceeds the thermal speed \( v_{th} = (kT/m)^{1/2} \). Those electrons travelling at greater than a critical speed \( v_c \approx (n_e/E)^{1/2} \) set by \( F_{\text{accel}} > F_{\text{drag}} \), will be accelerated to high speeds, a process called “runaway”. If the electric field exceeds the Dreicer field, \( E > E_D = 4\pi e^2 \ln \Lambda /kT \) (Holman 1985), then all electrons will runaway, but this rarely occurs because large \( E \) fields produce turbulence and anomalous resistivity (Norman & Smith 1978).

When \( E < E_D \) only those electrons in the tail of the Maxwell-Boltzmann velocity distribution, \( f(v) \), with \( v > v_c \) are accelerated. In this “sub-Dreicer regime”, the ratio of nonthermal to thermal electrons is \( N_{\text{nonth}}/N_{\text{th}} \approx \int_{v_c}^{\infty} f(v)dv/\int_{0}^{\infty} f(v)dv \). When \( E \ll E_D \), \( N_{\text{nonth}}/N_{\text{th}} \approx 0.5e^{-0.5(E_D/E)^{3/2}-E/E_D} \) (Norman & Smith 1978). In addition to accelerating electrons, electric fields can heat the plasma by several mechanisms, the simplest being the Joule heating rate \( iE = \dot{P}r \), where \( i \) is the current and the resistance \( r \) can be anomalous due to current-driven instabilities. Holman (1985) developed the theory of heating and acceleration by electric fields in the context of solar flares. For the example of \( T = 10^7 \) K, \( B = 300 \) G, and \( EM = 10^{45} \) cm\(^{-3} \), he finds that the time scales for Joule heating and acceleration of \( 10^{32} \) electrons are both about 30 seconds and the energy that goes into particle acceleration is always less than the heating rate. In his Case I, the assumption of \( E = 0.03E_D \) corresponds to \( v_c = 5.8v_{th} \), electron acceleration to maximum energy \( W_{\text{max}} = 10 \) MeV, and \( N_{\text{nonth}}/N_{\text{th}} \approx 3.4 \times 10^{-8} \). In his Case II, doubling the electric field strength to \( E = 0.06E_D \) results in \( v_c = 4.2v_{th} \), \( W_{\text{max}} = 100 \) keV, and \( N_{\text{nonth}}/N_{\text{th}} \approx 1.5 \times 10^{-4} \). Thus the \( N_{\text{nonth}}/N_{\text{th}} \) ratio and the maximum energy of the nonthermal electrons both depend very strongly on \( E/E_D \), but in the opposite sense.

Since gyrosynchrotron radiation is broad band with \( \Delta \nu \approx 1 \times 10^{10} \) Hz, the ratio of radio to X-ray emission ratio is \( R = L_R\Delta \nu /L_X = 10^{-5.5+0.5} \), much less than unity as predicted by Holman (1985). Since the gyrosynchrotron radio emission rate per relativistic electron is proportional to its energy squared, the main contribution to \( L_R\Delta \nu \) will be from the highest energy electrons. Free-free X-ray emission from \( T = 10^7 \) K electrons is proportional to \( N_{\text{th}}^2 V \). Thus \( R \) is proportional to \( (N_{\text{nonth}}/N_{\text{th}})W_{\text{max}}^2 V_f/N_{\text{th}}V \), where \( V \) is the volume of the thermal gas from which the nonthermal electrons have been swept up and \( V_f \) is the volume of the nonthermal electrons in the current channel. For Holman’s Case I, \( V_f/V \approx 10^{-1} \) and \( R \approx 3.4 \times 10^{-8}(10^7\text{eV})^210^{-3}/10^{10}\text{cm}^{-3} = 3.4 \times 10^{-7} \). For Case II, \( V_f/V = 1/200 \) and \( R \approx 1.5 \times 10^{-4}(10^5\text{eV})^2(1/200)/10^{4.1} \text{cm}^{-3} = 0.75 \times 10^{-7} \). The similar ratios for the two theoretical cases, despite the very different \( N_{\text{nonth}}/N_{\text{th}} \) values, show that DC electric fields can produce both runaway electrons in the sub-Dreicer regime and Joule heating consistent with a constant \( L_R/L_X \) relation.
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