High-Energy Phenomena in Magnetic CP Stars as Revealed by their X-Ray and Radio Emission

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Abstract. Before 1985, attempts to detect radio or X-ray emission from Magnetic CP (MCP) stars were either fruitless or ambiguous. However, more successful results have been obtained in the last dozen years: (i) Radio emission has now been detected from $\sim$ 35 MCP stars of the Helium-peculiar and Silicon-strong subclasses, with a functional dependence of radio luminosity $L_R \propto T_{eff}^7 H_s^{1.2} P_{rot}^{-0.6}$, where T_{eff} is the effective temperature, H_s is the surface magnetic field strength, and P_{rot} is the rotational period; rotational modulation of the radio emission has also been observed for several MCP stars. All of this evidence suggests that it is the MCP stars themselves, not close companions, that are responsible for the radio emission; (ii) The X-ray emission properties of MCP stars are however still poorly characterized: although a moderate number ($\sim$ 18) have by now been associated with X-ray sources, the lack of a clear correlation of this X-ray emission with other stellar parameters has made it difficult to rule out the close companion hypothesis.

Key words: stars: chemically peculiar – radio continuum: stars – X-rays: stars

1. Introduction

Magnetic chemically peculiar stars (hereafter MCP stars) have been recognized as a distinct subclass of chemically peculiar (CP) stars since the 1960s. The strong (kiloGauss) and predominantly dipolar magnetic fields of these stars have been considered to be possible sites of high-energy phenomena, both thermal and non-thermal, for almost as long. The closed field regions of MCP stars can, due to the high magnetic pressure, clearly confine any ionized plasma that flows from the stellar surfaces, and interaction between such putative stellar winds and the strong magnetic fields might also result in the acceleration of ions to extremely large energies. An important theoretical paper which clearly presented much of this physics was published by Havnes & Goertz in 1984 (q.v.). It was quickly realized that, since the stars with the higher effective temperatures have the strongest radiation-driven winds, the B-type MCP stars (i.e., the helium-peculiar and silicon-strong subclasses) were much more likely to exhibit high-energy phenomena than the 'classical' A-type MCP stars (i.e., the CrSrEu-strong subclass). Shore in a series of papers (Shore 1987; Shore *et al.* 1987; Shore

& Brown 1990) followed up on earlier work to propose that the He-pec stars had predominantly polar stellar winds as well as magnetospherically trapped plasma in the equatorial regions, and used this model to explain the variation with rotational phase of ultraviolet emission lines formed at temperatures $T_e \sim 10^5$K. Earlier papers (e.g., Groote & Hunger 1982) had fit the hydrogen Balmer lines of the He-strong star σ Ori E with a model in which plasma with $T_e \sim 10^4$K was confined in clouds in the equatorial regions.

In the present review, I will restrict my discussion to observations of MCP stars aimed at detecting plasma at temperatures $\gtrsim 10^6$K using X-ray telescopes, and to observations to detect high-energy, thermal or nonthermal electrons using radio telescopes. Thus, these studies can be regarded as complementing the aforementioned optical and UV studies that have helped to constrain the characteristics of the cooler components of the circumstellar plasma. I will briefly review the early studies in the radio and X-ray energy ranges and then discuss what has been newly learned in the last decade.

2. Radio Continuum Observations of MCP Stars

The first radio studies dedicated to MCP stars were those of Trasco *et al.* (1970) and Kodaira & Fomalont (1970). These and subsequent radio surveys in the 1970s were generally made using single-dish radio telescopes operating at cm wavelengths, and had spatial resolutions and positional accuracies of a few arcmin, and detection limits of 10 - 50 mJy, equivalent to radio luminosities L_R of 10^{17-18} erg s^{-1} Hz^{-1} at a distance of 100 pc. Trasco *et al.* failed to detect 3 MCP stars, including the well-studied Ap star α^2 CVn, while Kodaira & Fomalont also had no convincing detections in a sample of 12 MCP stars, although they did report a 50 mJy (2σ) excess at the position of the MCP star with the largest measured magnetic field, i.e., Babcock's Star or HD 215441. A few years later, Altenhoff *et al.* (1976) reported a further 13 non-detections of MCP stars in the radio band. These negative results, indicating that strong radio emission is not present in MCP stars, dampened interest in this field for almost a decade.

Radio astronomy was revolutionized in the late 1970s and 1980s by the start of operations of radio interferometers such as the Very Large Array (VLA) and the Australia Telecope Compact Array which have orders of magnitude improvement over single-dish telescopes in their sensitivity and angular resolution: observations with arcsecond accuracy and sub-mJy sensitivity became routine. For example, the VLA can detect a source of 0.1 mJy ($L_R \sim 10^{15}$ erg s^{-1} Hz^{-1} at 100 pc) at 3.6 or 6 cm in less than an hour, meaning that a survey 100 times deeper than the 1970s era programs could be done in less than a day. Also, measuring circularly polarized radio signals with the VLA is quite straightforward. Somewhat later, improvements in Very Long Baseline Interferometry (VLBI) techniques that culminated in the construction of the Very Long Baseline Array made radio observations with milliarcsecond spatial accuracy possible.

Somewhat embarrassingly, the first reliable radio detection of an MCP star was serendipitous: in the field of the 'normal' O9.5 V star σ Ori A, Dave Abbott and his collaborators detected a 3 mJy radio source that was spatially coincident with its visual companion, σ Ori E, a He-strong (HeS) MCP star. Stimulated by this discovery, a group of us surveyed 14 MCP stars, confirming that σ Ori E was a flat-spectrum radio source, and finding another MCP radio source, HR 1890 = HD 37017 (Drake *et al.* 1985). Both detected stars were HeS stars in the Orion OB1 Association that had measured kiloGauss (kG) photospheric magnetic fields, and had an implied $L_R \sim 6 \times 10^{17}$ erg s^{-1} Hz^{-1}. The flat spectral index of σ Ori E between 2 and 6 cm implied that the emission was either optically thin free-free (ff) or nonthermal in nature. An expansion of this VLA program to 34 MCP stars was reported by Drake *et al.* (1987) where 3 more radio detected MCP stars were listed, including a third HeS star, and two much later spectral type Si-type MCP stars, HD 215441 and IQ Aur. None of the later-type SrCrEu MCP stars were detected, however, with upper limits as low as 3×10^{14} erg s^{-1} Hz^{-1}, i.e., 3 dex lower than the radio luminosities of the HeS stars, in either the above study or a later one of Willson *et al.* (1988).

The 3 HeS stars appeared to form a rather homogeneous sample of high-luminosity radio emitters, and detailed studies of these stars showed that their radio fluxes were varying on a timescale of hours. This last property essentially clinched that the emission was nonthermal in nature, although another property of some types of nonthermal emission, viz. detectable levels of circular polarization, was not confirmed to be present in these radio sources. The other 2 radio-detected later-type stars were much weaker radio emitters ($L_R \sim 10^{16-17}$ erg s^{-1} Hz^{-1}) than the HeS stars and it was not clear whether their emission mechanisms were similar. Drake *et al.* 1987 proposed a schematic 'radiation-belt' model for the HeS radio emitters in which the radio emission was optically thick gyrosynchrotron emisison of mildly relativistic, nonthermal electrons that were sited in the closed-field magnetospheric regions at several stellar radii. This model required essentially continuous injection of nonthermal particles into the magnetospheric regions with a density profile that increased with radius so as to fit the observed radio spectra. Phillips & Lestrade (1988) confirmed the non-thermal nature of the HeS star radio emission using VLBI techniques when they failed to resolve the radio emission from 2 HeS stars, which enabled them to derive lower limits to the radio brightness temperatures of 10^9K that were inconsistent with thermal models.

Meanwhile, André *et al.* (1988, 1991) developed a model to explain an optically obscured, radio-emitting object (S1) in the ρ Oph star-forming region in which they suggested that it was a young MCP star. (Notice, however, that there is no other direct evidence that ρ Oph S1 is actually an MCP star). In this model, which would seem to be also applicable to the previously detected HeS star radio emitters, the radio emission was due to optically thin gyrosynchrotron emission from a torus of about 10 stellar radii, while the source of the nonthermal electrons was the magnetotail or current sheet formed where the predominantly polar stellar wind of this star terminates the closed-field magnetospheric regions. André *et al.* also argued that plasma in the inner magnetosphere would be heated to coronal temperatures, thus explaining the observed high (10^{31-32} erg s^{-1}) X-ray luminosity of this object. In their second paper, this group reported VLBI observations of S1 which implied a radio-emission region of ~ 6 stellar radii and a brightness temperature of 10^8K, and adjusted their model slightly to fit these new constraints.

Leone (1991) showed that the radio emission from σ Ori E and HR 1890 varies with the phase of the magnetic field (i.e., the rotational phase), and proposed a model in which the radio emission was due to gyroresonance emission from low-temperature ($T_e \ll 10^6$K) electrons in the polar wind regions. This model also predicted that the radio emission should exhibit zero circular polarization. Leone & Umana (1993) obtained more radio data on these two stars, strengthening the observed correlation with magnetic phase, and made a comparison of the rival models for MCP star radio emission.

Linsky *et al.* (1992) updated the Drake *et al.* (1987) VLA survey results, reporting detection of 3 out of 9 HeS stars (all in Orion OB1) with $\log L_R \sim 16.8 - 17.9$, 13 out of 38 HeW/Si stars (9 in Sco OB2) with $\log L_R \sim 14.7 - 17.2$, and 0 out of 14 cool Ap stars with $\log L_R < 14.7$. In addition, in 4 of the detected stars variable circular polarization at levels of up to 30% was detected, ruling out (at least in these cases) the gyroresonance emission model. Using both the radio detections and the significant non-detections, Linsky *et al.* found that the radio emission obeyed a global relation $L_R \propto \dot{M}^{0.4} B^{1.1} P_{rot}^{-0.3}$, where the mass-loss rate $\dot{M}$ was derived from the stellar effective temperature T_{eff} using a functional dependence derived by Lamers for normal (i.e., nonmagnetic) hot stars. They revised the Drake *et al.* (1987) model to one in which the emission (still attributed to optically thick gyrosynchrotron emission) originated in two tori above and below the magnetic equator, the radii of which increased with increasing wavelength from 3 stellar radii at 6 cm to ~ 10 stellar radii at 20 cm. They agreed with André *et al.* that the current sheet is the likely source of the nonthermal electrons, and, under this assumption, estimated the total magnetic energy content of the current sheet as $\propto \dot{M}^{0.7} B^{0.7} P_{rot}^{-1.3}$, i.e., rather similar to the functional dependence of the observed radio emission.

Leone *et al.* (1994) detected 3 more Si-type Bp stars as radio emitters and presented more evidence that the radio maxima for the well-observed systems occured at magnetic field extrema. Later, Leone *et al.* (1996) discussed the 1.3 to 20 cm radio spectra of 7 MCP stars, finding rather diverse spectral properties for these stars that imply that in some (but not all) MCP stars the radio emission is absent or suppressed in the inner magnetospheric regions. They also reported non-detections at 1.3 mm wavelength of 3 of the MCP stars.

Recently, Drake *et al.* (1998a) have detected 16 more HeW/Si star radio emitters, bringing the total number of known radio-emitting MCP stars to about 35, i.e., this is a well-established class of radio-emitting stars. Using a subset of 38 MCP stars for which well-defined fundamental parameters are available, 24 of which were detected as radio sources, and 14 of which were not, Drake *et al.* found an empirical relation that is accurate to $\sim \pm 0.6$ dex:

$$\begin{aligned}\log(L_R) \approx\ & 15.1 + (6.85 \times \log(T_{eff}/10^4)) + (1.20 \times \log(H_s/\mathrm{kG})) \\ & -(0.60 \times \log(P_{rot}/\mathrm{days}), \end{aligned} \quad (1)$$

where H_s is the effective surface magnetic field.

3. X-Ray Observations of MCP Stars

MCP stars have been proposed as possible counterparts to X-ray sources for at least 20 years (e.g., Groote *et al.* 1978, Cash *et al.* 1979), but it has proven unexpectedly hard to confirm them as a 'real' class of X-ray sources. This is partly because X-ray emission in stars is quite ubiquitous (with the possible exception of A-type stars), and, thus contaminating emission from low-mass binary companions is always a possible factor. Nevertheless, there were a handful of candidate MCP X-ray sources that were identified in *Einstein* and *EXOSAT* X-ray observations in the 1980s, e.g., Cash & Snow (1982), Cutispoto *et al.* (1990), but no obvious pattern of MCP star fundamental properties versus X-ray properties was evident. The MCP stars which might have been predicted to have the best chance of having intrinsic X-ray emission, viz. the HeS stars, do in fact appear to be X-ray emitters (cf. Drake *et al.* 1987), but only at levels that are similar to those seen in non-magnetic stars of the same spectral types, i.e., the HeS star X-ray emission appears to be related to the stellar wind region, and not to the magnetosphere. Thus, by 1990, MCP stars had still not been established as a class of intrinsic X-ray emitters, although there were some interesting 'suspects', e.g., some of the 12 B6-A3 stars in Ori OB1 that were detected as X-ray sources by Caillault & Zoonematkermani (1989) may be MCP in nature. Given that the X-ray emission properties of normal B3-A9 stars were not well-known at this time (except that their X-ray luminosities were too low to detect typically), better observations were clearly required.

The launch of the *ROSAT* X-ray observatory in 1990 revolutionized X-ray astronomy, primarily due to its being 10-100 times more sensitive than earlier X-ray observatories: now, stars with $\log L_X \geq 28.0$ only slightly stronger than that of the Sun ($\log L_X \sim 27.3 \pm 0.5$) could easily be detected at distances of up to 100 pc. This enormously increased the number of MCP stars which could be searched for X-ray emission. The subsequent launch in 1993 of the *ASCA* X-ray observatory enabled, for the first time, moderate-resolution X-ray spectroscopy ($E/\Delta E \sim 30$ compared to ~ 3 for *ROSAT*) to be performed on such weak X-ray sources as MCP stars appear to be.

A theoretical paper which appeared around this time (Usov & Melrose 1992) proposed that the X-ray emission observed in luminous (nonmagnetic) OB stars was in fact due to a current sheet formed between the known strong stellar winds of these stars and hypothetical small magnetospheres (with implied photospheric field strengths of $\sim$ 100 Gauss lying below present detection limits). The predicted functional dependence of X-ray emission on fundamental properties for this mechanism, viz., $L_X \propto \dot{M}^{9/4} V_{wind}^{-3/4} H_s^{-1/2} R_*^{-3/2}$, means that, extrapolating this model to the relatively low mass flux and high magnetic field MCP stars, X-ray luminosities at undetectable levels ($\log L_X \sim 23 - 24$) are predicted. However, it should be noted that (a) this model does not appear to be widely accepted as applying to nonmagnetic hot stars, and (b) its extrapolation to MCP stars may be rather risky.

Despite this caveat, Drake *et al.* (1994) studied the *ROSAT* All-Sky Survey X-ray database at the positions of $\sim$ 100 radio-observed MCP stars, with a detection level of $\log L_x \sim 29.4$ at 100 pc (note that this is significantly poorer than that achievable in pointed *ROSAT* observations). After eliminating a handful of cases in which binary companions to MCP stars seemed the more likely candidates for being the X-ray emitters, only 6 out of 100 MCP stars (2 of which are HeS stars and the remainder are HeW/Si stars) seemed to be candidates for being intrinsic X-ray emitters, a very low detection rate not inconsistent with a true rate of 0%. They concluded that MCP stars are clearly not a class of X-ray emitters at levels in excess of $\log L_X \sim 30$, and furthermore found no evidence that there was any correspondence between radio and X-ray emission in these stars, in that many radio-bright stars were not detected as X-ray sources (and *vice versa*). A similarly low detection rate was reported by Leone (1994) based on a re-examination of the archival *Einstein* data on MCP stars: he found only 4 out of 90 MCP Bp stars were detected as X-ray sources, but noted that 3 of these 4 stars were actually binary systems.

Subsequent to this, only a few other papers on this subject have appeared: perhaps the most interesting being (a) the *ROSAT* studies of the young (10^8 years) open cluster NGC 2516 by Dachs & Hummel (1996) and Jeffries *et al.* (1997) in which 4-6 of the known MCP stars in this cluster were detected as X-ray sources (the second paper concluded that this emission was probably intrinsic, although binary companions cannot be entirely ruled out), and (b) the discovery by Gagné *et al.* (1997) of X-ray emission from the Orion Trapezium star θ^1 Ori C that varies periodically on a 15 day timescale: these authors suggested that this O7 V star could be a high-mass example of an MCP star (but this star has not, of course, been otherwise proven to be an MCP star). In some of my unpublished work (Drake *et al.* 1998b), I have extended the program of Drake *et al.* (1994) to include archival pointed *ROSAT* observations, and have about 18 candidates among MCP stars for intrinsic X-ray emission, including Babcock's Star (with $\log L_X \sim 29.2$) and 13 other HeW/Si stars, and 4 SrCrEu-type stars. Despite the increase in this sample size, there is still little evidence that the X-ray emission of these stars correlates with any other known property, meaning that it is still impossible to predict which MCP stars will be X-ray emitters *a priori*. The logarithmic ratio of the X-ray to the radio emission varies from < 11.9 to 14.5, for example, which should be compared to the value

$\log(L_X/L_R) \sim 15.0 \pm 0.5$ found for active late-type stars with similar radio luminosities to those of the MCP stars. Thus, all MCP stars appear to be X-ray weak relative to their radio emission strength compared to the late-type stars: this is not a trivial comparison, because it should be noted that the mechanism for the production of the radio emission in both of these classes of stars, i.e., optically thick gyrosynchrotron emission from mildly relativistic electrons, is essentially the same, although the geometry is certainly different.

In Drake *et al.* (1998b), X-ray spectra of some of these candidate X-ray emitting MCP stars are also discussed. These spectra look, in general, very similar morphologically to the X-ray spectra of other classes of stars, i.e., there is nothing unusual in MCP star X-ray spectral shapes that could be used as a discriminator. One exception is the *ROSAT* spectrum of the Si star HR 5624, which appears to be best fit with a Si abundance in the X-ray emitting plasma of ~ 15 times the solar photospheric value and which is similar to the levels of overabundance of Si in the photospheres of Si stars. In a follow-up *ASCA* observation of this same star obtained a couple of years later, I derived a much lower Si overabundance (about twice solar): notice, however, that due to the lower sensitivity of *ASCA* compared to *ROSAT*, this second observation was essentially an average over an entire rotational phase of this rapidly rotating star ($P_{rot} = 0.88$ days), whereas the *ROSAT* observation was made over only a small fraction of the phase. Thus, the possibility that the X-ray emitting plasma may be overabundant in Si in a time-variable way cannot be ruled out.

4. Conclusions

There is an essential difference between the radio and the X-ray properties of the MCP stars, with the former being well-established and the latter quite the opposite. Nonthermal radio emission is prevalent among the B-type MCP stars, and the basic emission mechanism is almost certainly gyrosynchrotron emission from mildly relativistic nonthermal electrons. Their radio emission properties are predictable from their basic properties (cf. eq. 1), and, in general terms, explainable using current models, although detailed models which fit the radio spectra and circular polarizarion as a function of aspect for specific stars are still pending. Their X-ray emission properties are still uncertain: the existence of significant amounts of plasma at $\gtrsim 10^6$K has still not been confirmed to be a common feature in MCP stars despite 20 years of observations. The presence of X-ray emission is not predictable from either their MCP type or their radio properties. In this sense, their status as a class of intrinsic X-ray emitters is, in my opinion, still not demonstrated. If the existing candidate X-ray emitters are intrinsic, then a revision of the Usov & Melrose (1992) model is clearly required, since, in its present form, it is underpredicting the X-ray luminosities by 7 or 8 orders of magnitude. Conclusive evidence for the intrinsic hypothesis might be (a) the discovery of a distinct X-ray spectral signature, such as elemental abundances showing a similar pattern to the underlying photospheric abundances, or (b) the finding of an X-ray modulation with a similar period to that of the magnetic light-curve, or (c) the acquisition of enough X-ray detections among MCP stars that a correlation with some other stellar properties may be found.

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References

Altenhoff, W., Pfleiderer, J. & Weiss, W.: 1976, in *Physics of Ap Stars*, ed.: W.W. Weiss, H.H. Jenkner & H.J. Wood, Reidel, Dordrecht, 497
André, P. *et al.*: 1988, *Astrophys. J.* **335**, 940
André, P. *et al.*: 1991, *Astrophys. J.* **376**, 630
Caillault, J.P. & Zoonematkermani, S.: 1989, *Astrophys. J., Lett. Ed.* **338**, L57
Cash, W. & Snow, Jr., T.P.: 1982, *Astrophys. J., Lett. Ed.* **263**, L59
Cash, W., Snow, Jr., T.P. & Charles, P.: 1979, *Astrophys. J., Lett. Ed.* **232**, L111
Fernandèz, J.A.: 1982, *Astron.J.*, **87**, 1318
Cutispoto, G., Tagliaferri, G. & Catalano, F.A.: 1990, *Inf. Bull. Variable Stars*, No. 3542
Dachs, J. & Hummel, W.: 1996, *Astron. Astrophys.* **312**, 818
Drake, S.A. *et al.*: 1985, in *Radio Stars*, ed.: R.M. Hjellming & D.M. Gibson, Reidel, Dordrecht, 247
Drake, S.A. *et al.*: 1987, *Astrophys. J.* **322**, 902
Drake, S.A. *et al.*: 1994, *Astrophys. J.* **420**, 387
Drake, S.A. *et al.* 1998a, in preparation
Drake, S.A. *et al.* 1998b, in preparation
Gagné, M. *et al.*: 1997, *Astrophys. J., Lett. Ed.* **478**, L87
Groote, D. & Hunger, K.: 1982, *Astron. Astrophys.* **116**, 64
Groote, D., Kaufmann, J.P. & Hunger, K.: 1978, *Astron. Astrophys.* **63**, L9
Havnes, O. & Goertz, C.K.: 1984, *Astron. Astrophys.* **138**, 421
Jeffries, R.D., Thurston, M.R. & Pye, J.P.: 1997, *Mon. Not. R. Astron. Soc.* **287**, 350
Kodaira, K. & Fomalont, E.B.: 1970, *Astrophys. J.* **161**, 1169
Leone, F.: 1991, *Astron. Astrophys.* **252**, 198
Leone, F.: 1994, *Astron. Astrophys.* **286**, 486
Leone, F., Trigilio, C. & Umana, G.: 1994, *Astron. Astrophys.* **283**, 908
Leone, F. & Umana, G.: 1993, *Astron. Astrophys.* **268**, 667
Leone, F., Umana, G. & Trigilio, C.: 1996, *Astron. Astrophys.* **310**, 271
Linsky, J.L., Drake, S.A. & Bastian, T.S.: 1992, *Astrophys. J.* **393**, 341
Phillips, R.B. & Lestrade, J.F.: 1988, *Nature* **334**, 329
Shore, S.N.: 1987, *Astron. J.* **94**, 731
Shore, S.N. & Brown, D.N.: 1990, *Astrophys. J.* **365**, 665
Shore, S.N., Brown, D.N. & Sonneborn, G.: 1987, *Astron. J.* **94**, 737
Trasco, J.D., Wood, H.J. & Roberts, M.S.: 1970, *Astrophys. J., Lett. Ed.* **161**, L129
Usov, V.V. & Melrose, D.B.: 1992, *Astrophys. J.* **395**, 575
Willson, R.F., Lang, K.R. & Foster, P.: 1988, *Astron. Astrophys.* **199**, 255