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Stellar Coronae: New Insights into Fundamental Questions

Jeffrey L. Linsky

JILA, University of Colorado and NIST, Boulder, CO 80309-0440

Tom Ayres, Alec Brown, Rachel Osten, and Steve Skinner

CASA, University of Colorado, Boulder, CO 80309-0389

Marc Gagné

West Chester University, West Chester, PA 19383-2130

Abstract. We summarize the fundamental questions of stellar coronal physics that Chandra and XMM-Newton will attempt to answer with emphasis on the coronae of brown dwarfs and O stars and the anomalous abundances observed in stellar coronae.

1. The Fundamental Questions of Stellar Coronal Physics

The Chandra and XMM-Newton missions have opened a new era of stellar astrphysics — one characterized by high resolution spectroscopy and imaging, high throughput, low background, and long duration observations of transient sources uninterrupted by Earth occultations. These unprecedented capabilities, especially the spectroscopy, provide a unique opportunity to answer many fundamental questions about stellar coronae that previous missions (e.g., Einstein, EXOSAT, ROSAT, ASCA) posed but could not answer. We list some of these questions and in the limited space below describe what insights Chandra and XMM-Newton are providing concerning several of these questions:

Terminology: What are the critical phenomena or properties that characterize the hot ionized plasma around a star that we call a corona? Do only late-type stars have such properties? Are magnetic fields required? Do X-ray binaries have coronae?

Existence: What types of stars show evidence for coronae? Do hot stars have coronae? Do brown dwarfs have coronae? Do M supergiants have coronae?

Binarity: How does the presence of a nearby companion star determine the properties of a stellar corona?

Geometry: What are the important structures in a corona? How extended are coronae? Are the structures magnetically confined?

X-ray luminosity: How does L_X correlate with $v\sin i$, P_{rot}, age, and other physical parameters? When and why does saturation occur? What is supersaturation? How small can L_X and F_X be in a corona?

Physical properties: What are typical emission measure distributions and thermal–density structures in coronae? Single and binary stars with quite different physical properties nevertheless have similiar physical properties. What is this telling us about the energy balance in stellar coronae?

Nonthermal plasma: Hard X-rays ($E > 10$ keV) are seen in solar flares and in a few cases during stellar flares. Is this emission produced by nonthermal or very hot ($T > 10^8$ K) electrons? Why are gyrosynchrotron radio and thermal bremsstrahlung X-ray emission correlated?

Abundances: Metals with first ionization potentials < 10 eV are overabundant in the solar corona (the FIP effect) but underabundant in the coronae of active stars. Is this inverse FIP effect real? What plasma physics and/or MHD processes lead to this wierd behavior?

Ionization: How valid is the assumption of steady-state coronal ionization equilibrium? How important are radiative processes?

Flares: Is a self-consistent physical model for a flare that explains the rich set of observables and has predictive power?

Dynamics: What flows (downward and upward) occur in stellar coronae? Does only the coolest coronal plasma expand as a wind?

Magnetic fields: What roles do magnetic fields play in stellar coronae?

Energy source: What mechanism(s) provide energy (thermal, kinetic, nonthermal particles) into the corona of different types of stars? Can nonmagnetic processes be important in some stars?

2. What types of stars show evidence for coronae?

The conventional wisdom is that all stars with convective zones below their photospheres create turbulent magnetic fields through a dynamo process that heat a coronae either through field reconnection events (flares both large and small) or the dissipation of MHD waves. According to this picture one expects all main sequence stars from spectral type late-A to late-M, giants of intermediate spectral type, rapidly rotating binaries with a late-type companion (e.g., RS CVn, W UMa, and Algol types), and the fully convective premain sequence stars will have coronae. Einstein, ROSAT, and ASCA observations support this picture. The ROSAT All Sky Survey detected all F and G dwarfs within 13 pc and all K and M dwarfs within 7 pc with $\log L_X$ in the range 26.5–33, while detecting no A stars earlier than spectral type A7 (e.g., Schmitt 1997; Hünsch et al. 1999). Flares are seen in essentially all of these spectral types, indicating rapid conversion of magnetic energy into heat. Chandra and XMM-Newton are extending the classes of observed X-ray emitting stars.

2.1. Do brown dwarfs have coronae?

Brown dwarfs (BDs) are fully convective stars with masses ($M/M_{\odot} < 0.08$) smaller than required for long-term hydrogen burning. They should have dynamo-generated magnetic fields (like Jupiter and the late M dwarfs), but no magnetic fields have yet been measured in BDs. Hα emission has been reported during flares in two BDs, and one appears to flare < 7% of the time. Berger et al. (2001) detected radio emission from a BD (LP944-20), very weak 8.46 GHz emission outside of flares and strong emission during flares. Gyrosynchrotron emission indicates weak (5 G) magnetic fields in the corona. In the ROSAT data the lowest mass main sequence star with detected steady X-ray emission is VB8 (M7 Ve), and the lowest mass star with detected X-ray emission during a flare is the M8 V star VB10. Two pre-main sequence BDs (and four BD candidates) have been detected as ROSAT X-ray sources in young star forming regions. Accretion could be an energy source for these young objects.

Using the Chandra ACIS-S, Rutledge et al. (2000) were able to detect faint X-ray emission during a flare on LP 944-20, a relatively old ($t = 500$ Myr) isolated, nonaccreting BD on the main sequence. X-rays were detected during a flare (peak $\log L_x = 26.0$), with duration about a 10% of the observing time, but not outside of the flare ($\log L_x < 24.0$).

The new Chandra observations suggest an emerging paradigm. Young BDs are like the higher mass T Tauri stars — their quasi-steady and flare X-ray and radio emission are produced in permanent coronae that are heated by accretion and/or the interaction of strong stellar and disk magnetic fields. Old BDs, however, show Hα and X-ray emission only during giant flares. They have either no permanent coronae or coronae with extremely low emission measures with rare detectable flares. Note the trend of decreasing L_X(non-flare) with decreasing $M/M_{\odot}$ and M_V. A sensible speculation is that the weak convection resulting from the absence of a nuclear energy source in the stellar core can only support a distributed (α^2) dynamo that produces weak disordered magnetic fields with a very different geometry than for the M dwarfs.

2.2. Do O stars have coronae?

The observed relation $L_X \approx 10^{-7} L_{\rm bol}$ for single O stars is usually explained by shocked plasma produced by radiative instabilities in their high speed (≈ 1000 km/s) radiatively-driven winds. For recent models see Owocki et al. (1988) and Feldmeier (1995). Close binaries containing O and WR stars have colliding winds with strong X-ray emission and nonthermal radio emission. The small amount of soft X-ray absorption seen in hot star data supports the idea that the emission comes from throughout the wind, but the real test is the temperature of the hot gas. This measurement requires X-ray spectroscopy.

The Chandra HETG spectrum of ζ Orionis (O9.7 Ib) analyzed by Waldron & Casinelli (2001) challenges the shocked wind model in several ways: (1) Electron densities determined from the He-like ions are largest for the hottest ion (Si XIII), indicating that the hottest gas is located deep in the corona where the wind speed is small. Radiatively driven wind theory, on the other hand, predicts that the hottest lines should be produced where the wind speed is largest, which is far from the star. (2) The theory predicts that the centroids of emission lines should be blue-shifted, but no systematic Doppler shifts are seen. (3) The observed line shapes are all Gaussian (FWHM 900 ± 200 km/s) in shape contrary to predicted line shapes for optically thick or thin winds.

Analysis of the XMM-Newton spectrum of ζ Puppis (O4 Ief) by Kahn et al. (2001) shows that the lowest temperture ions (N VI and O VII) have the broadest widths, indicating that they are formed furthest from the star where the wind speed is largest. This is also consistent with the hottest gas being located deep in the corona. Chandra HETG spectra show emission lines from Fe XXIV and Fe XXV, located in coronal gas as hot as 6×10^7 K. Densities greater than 10^{12} cm^{-3} are inferred from helium-like Mg XI. Schultz et al. (2000) argue that this very hot, dense plasma must be confined in magnetic loops in the corona, probably located near the base of the wind. It is difficult to measure magnetic fields in O stars directly, but fields are inferred from the gyrosynchrotron radio emission (e.g., Bieging et al. 1989) and discrete absorption components in UV emission lines that are interpreted as magnetic structures in the wind (e.g., Howarth et al. 1995). Wade and Donati (in preparation) are now directly measuring the presumably fossil magnetic fields in the O6 star θ^1 Ori C.

These new observations suggest a fusion of the shocked wind and stellar corona paradigms. Part of the X-ray emission is likely formed in the wind, but the hottest plasma is confined and heated in magnetic loops near the base of the wind. If we assume that the plasma is confined, that is $\beta = P_{gas}/P_{mag} \geq 1$ and $n_e = 10^{12}$ cm^{-3}, then $B \geq 180$ G. Thus O star coronae share some characteristics with the coronae of cooler stars with convective zones. Future studies should be directed to testing models of magnetic loops and comparing observed and theoretical X-ray line profile shapes to test a new generation of sophisticated radiative transfer models for stellar winds. (e.g., Owocki & Cohen 2001).

3. Coronal Abundances

Why do stellar coronal abundances often differ appreciably from photospheric abundances, and what physical processes cause these abundance anomalies. The Table summarizes the observational situation. Solar coronal abundances (see the excellent review by Feldman & Laming 2000) depend on the magnetic field structure, how long the plasma has been in this structure, and the first ionization potential (FIP) of the element. Elements with FIP $<$ 10 eV (e.g., Mg, Si, and Fe) generally behave differently from elements with FIP $>$ 10 eV (e.g., O, S, Ne, and Ar). The term "FIP bias" or "FIP effect" refers to the enhancement of the low FIP ions relative to their photospheric values. Coronal holes with their open magnetic field structure and the high speed solar wind that originates there show photospheric abundances, but coronal plasma in closed magnetic loops and in the slow speed wind show a FIP bias of 4–5, that is the abundances of low-FIP ions are enhanced by this factor while high-FIP ions are photospheric. Newly emerging or flare "evaporated" plasma from below initially has photospheric abundances, but in magnetic loops the FIP bias increases linearly with time, reaching 4 in 2 days and a maximum value of about 15 for very old loops. In large magnetic structures (i.e., streamers) Fe is a factor of 3 weaker than other low-FIP ions, perhaps due to gravitational settling.

Coronal Structure	Low-FIP [X/H]	Time variation of low-FIP	High-FIP [X/H]	Magnetic Field
		Solar Corona		
High speed SW	0.0		0.0	open
Slow speed SW	+0.6		0.0	mixed
New coronal plasma	0.0	increases	0.0	closed
Coronal loops	+0.6	$\Rightarrow$+1.7	0.0	closed
Coronal holes	0.0		0.0	open
Fe at $R > R_\odot$	+0.6	$\Rightarrow$0.0	0.0	closed
		Pre-Chandra/XMM Results		
Solar-like stars	+0.6		0.0	$f \leq 0.1$
AB Dor	–0.4		–0.4	large f
Capella	0.0		0.0	
II Peg	–0.5		0.0	large f
II Peg (flare)	0.0	decreases	0.0	
UX Ari	–0.5		0.0	large f
UX Ari (flare)	0.0	decreases	0.0	
σ^2 CrB	-0.6			large f
σ^2 CrB (flare)	0.0	decreases		
		Chandra/XMM Results		
HR 1099 (HETG)	–0.5		+0.7	large f
HR 1099 (RGS)	–0.6		+0.6	large f
AB Dor (HETG)	–0.5		+0.1	large f
AB Dor (RGS)	–0.6		0.0	large f
AB Dor (RGS)(flare)	0.0	decreases		

EUVE and ASCA first identified different FIP biases for active stars, but the high spectral resolution and S/N of Chandra and XMM-Newton are required to separate emission lines from the continuum, which is needed to determine the H abundance and thus abundances relative to H. Analysis of EUVE spectra of inactive stars like α Cen AB (G2 V + K1 V), ϵ Eri (K2 V), and ξ Boo A (G8 V) show a solar-like FIP bias (e.g., Drake & Kashyap 2001), whereas active stars like AB Dor (young K dwarf) and the RS CVn binaries II Peg, UX Ari, and σ^2 CrB show low-FIP Fe depleted by factors of 3–4 compared to the photosphere (Mewe et al. 1996, 1997; Güdel et al. 1999; Osten et al. 2000). During flares the coronal abundances approach photospheric values, presumably due to gas from low in the atmosphere being ionized by the flare. After the flares the abundances return to their reverse-FIP bias. Capella, perhaps an intermediate case, shows no FIP bias. Could these interesting results be spurious given the low S/N and spectral resolution of the EUVE and ASCA data?

The RS CVn system HR 1099 was observed by the Chandra LETG (Drake et al. 2001) and the XMM-Newton RGS (Brinkman et al. 2001). Both studies find a reverse-FIP bias with Fe/H 0.25 times its solar photospheric value and the high-FIP elements Ne and Ar overabundant by more than a factor of 10.

Güdel et al. (2001) also find low-FIP elements underabundant in AB Dor and photospheric abundances during a flare, confirming the earlier picture.

How can we make sense out of this complex picture of FIP and reverse-FIP biases? The following may be the seeds of a plasma physics explanation:

- Element separation producing the solar FIP effect probably occurs in the chromosphere where low-FIP elements are ionized and the high-FIP elements are neutral. The high-FIP elements diffuse out of the magnetic flux loops and the enhanced low-FIP plasma rises into the corona. In open field regions (solar coronal holes and high-spead streams) this loss of high-FIP neutrals does not occur and there is no FIP bias.
- In very active stars, strong magnetic fields fill the whole surface (the filling factor f approaches 1.0). Therefore, high-FIP neutrals leak out of one flux tube into another, so that there is no loss of high-FIP elements. Since L_X is very large, X-rays photoionize the elements with high-FIP and large photoionization cross-sections, especially Ne and Ar. This may play a role in explaining the inverse FIP effect, but the full explanation is unclear.

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