X-RAY CORONAE OF STARS: RECENT RESULTS FROM CHANDRA

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ABSTRACT

I summarize and comment upon studies of stellar coronae using the remarkable spectroscopic and imaging capabilities of the Chandra X-ray Observatory. Nearly all types of stars are detected as X-ray sources, except for the late-B to early-A stars and the cool giants and supergiants. Chandra's high resolution spectroscopy provides emission measure distributions, electron densities, coronal abundances, and tantilizing hints about the structure and evolution of stellar coronae. Chandra's high resolution imaging is resolving the crowded fields of young clusters into their constituent stars from massive O stars to brown dwarfs.

THE JOYS AND PAINS OF CHANDRA

Since its launch on 1999 July 23, The Chandra X-ray Observatory has provided unique data sets with unprecedented spectral and spatial resolution. As a result of their unprecedented quality, these new data have stimulated a major advance in our understanding of stellar coronae. In this review I will summarize the highlights of these new results and comment upon why they are important and what implications these results may have on future studies. Let's begin with an appreciation of Chandra's new capabilities.

For the First Time Moderate Resolution X-ray Spectroscopy

Since all previous X-ray satellites (e.g., HEAO-1, Einstein[2], EXOSAT, ROSAT, and ASCA) had low energy resolution, $\Delta E \geq 150$ eV, one could not measure the fluxes of individual emission lines or separate the continuum accurately from the emission lines. This inevitably led to uncertain differential emission measures (DEM), simple 1-T or 2-T coronal models, no measurements of electron densities, no information on mass motions, and inaccurate abundances relative to hydrogen (as inferred from the free-free continuum). By comparison, Chandra's HETG has a resolution $E/\Delta E \leq 1000$ ($\Delta v \geq 300$ km s^{-1}) covering the 2–25 Å spectral range (0.5–8 keV energy range), and Chandra's LETG has a resolution $E/\Delta E \leq 1500$ ($\Delta v \geq 200$ km s^{-1}) covering the 2–170 Å spectral range (0.073–6.2 keV energy range). Chandra's spectral resolution is sufficient to separate many important emission lines from the continuum and nearby lines. Thus one can determine the coronal DEM distribution more accurately and measure line fluxes relative to the continuum, leading to abundances relative to hydrogen. Chandra's spectral resolution is sufficient to separate the density sensitive triplet lines of helium-like ions. Furthermore, the LETG and HETG can observe a very broad spectral range at one time, which is critically important for studying transient sources (e.g., flaring stars). The spectral resolution is not sufficient, however, to resolve the line profiles (e.g., the predicted thermal FWHM = 75 km s^{-1} for Fe lines formed near $\log T = 6.8$). It is also difficult to measure Doppler shifts, although there are success stories (see below).

While XMM-Newton has a somewhat lower resolution than Chandra, the RGS data with $\Delta v \geq 400$ km s^{-1} allow one to measure many individual spectral lines and to infer coronal electron densities (cf. review paper

[2] The Bragg crystal spectrometer on Einstein had high spectral resolution, but studied few sources due to its low throughput.

by Audard in this volume). At much lower resolution, EUVE measured many coronal emission lines in the 80–370 Å range including Fe XXI lines, which provide estimates of coronal electron densities. At much higher resolution a few coronal emission lines can be resolved by FUSE, which can study the Fe XVIII 977 Å coronal line with 15 km s^{-1} resolution (Redfield et al. 2003), and by HST/STIS, which can study the Fe XII 1242 and 1349 Å lines and Fe XXI 1354 Å line with 7 or even 3 km s^{-1} resolution (Ayres et al. 2003).

For the First Time High Quality X-ray Imaging

The half power diameter was about 10$''$ for Einstein, 8$''$ for ROSAT, 180$''$ for ASCA, and is 6$''$ for XMM-Newton. With such resolutions, it is difficult to determine which star in an error box is the X-ray source. This is especially important for crowded fields like young clusters (e.g., Orion and M16/Eagle Nebula). Since most stars are binaries, high resolution is needed to determine which star (or both) is the X-ray source. By contrast, Chandra's mirror assembly has half power imaging diameters: 0$''$.5 at 0.277 keV and 0$''$.7 at 6.4 keV. With crisp subarcsecond resolving power and knowledge of the aspect and plate scale distortions typically to better than 1$''$, one can accurately superimpose deep optical and IR images on to the Chandra images. High angular resolution reduces the background per pixel. A factor of 10 reduction in FWHM reduces the background per pixel by a factor of 100! For Chandra, six photons is a reliable detection!

For the First Time Long Duration Observing without Interruptions

With its 4 day orbital period, Chandra can monitor transient sources continuously for long periods of time without Earth occultations. This capability is very important for studying flares and phase-dependent phenomena with high observing efficiency. Also, Chandra's infrequent Earth occultations and passages through the Earth's radiation belts make it easier to schedule coordinated observing programs.

However, Chandra's data reduction and analysis software is very complex with a steep learning curve.

RECENT PUBLICATIONS AND RESULTS

Close Binaries

Capella (G1 III + G8 III, P_{orb} = 104 days)

Capella, the X-ray brightest late-type spectroscopic binary system, is moderately active with $L_x/L_{bol} = 2 \times 10^{-5}$, and $\log L_x$ (ergs s^{-1}) = 30.6. Canizares et al. (2000) and Brinkman et al. (2000) analyzed the rich Chandra HETG and LETG spectra to infer DEM distributions, coronal abundances, and estimates of n_e using the O VII triplet line ratios. The DEM peaks at T =(5–7)$\times 10^6$ K (Phillips et al. 2001), similar to the decay phase of many solar flares. Although Canizares et al. (2000) and Behar, Cotton, and Kahn (2001) found a broad range of coronal temperatures, the DEM peak temperature found by Phillips et al. (2001) is similar to that previously derived from low resolution EUVE and ASCA data (Brickhouse et al. 2000). From an analysis of Capella's LETG spectrum, Mewe et al. (2001) also found a similar peak temperature but the shape of the DEM is quite different from other analyses, which is important for deriving accurate abundances. They found that the abundance ratios O/Fe and Ne/Fe are similar to the solar photosphere and that N/Fe, Mg/Fe, and Si/Fe are about twice solar. Thus the moderately active Capella system shows neither a first ionization potential (FIP) bias (overabundance of low FIP elements in the corona) nor an inverse-FIP bias. (See Feldman and Laming 2000 and the paper by J. Drake in this volume for a summary of observed coronal abundance anomalies and proposed theoretical explanations.)

Table 1. Electron Density Estimates for Capella

Ion	Grating	(i/f)	$n_e(10^9$ cm$^{-3})$	Reference
O VII	HETG	0.35 ± 0.05	8–20	Canizares et al. (2000)
O VII	LETG	0.250 ± 0.035	≤ 5	Brinkman et al (2000)
O VII	HETG	0.38 ± 0.080	17 (± x2)	Phillips et al. (2001)
O VII	LETG	0.28 ± 0.05	1–10	Mewe et al. (2001)
O VII	LETG	0.255 ± 0.015	0.5	Ness et al. (2002a)
Fe XX-XXII	LETG	–	$\sim 10^3$	Mewe et al. (2001)

In two important papers, Ness et al. (2001, 2002a) explored the accuracy with which ratios of the triplet lines (resonance, intersystem, and forbidden) (r, i, f) of helium-like ions can be used to infer coronal electron densities. The lines of the lower temperature ions [C V (40 Å) and N VI (29 Å)] are best studied with the LETG, whereas the higher temperature ions [O VII (22 Å), Ne IX (13.6 Å), Mg XI (9.2 Å), and Si XIII (6.7 Å)] are best studied with the HETG. The accuracy with which one can measure electron densities from the i/f line ratios is limited by: (a) the ratios are often close to their low density limits, (b) the flux of the weak i line is often only slightly stronger than the background, (c) photoexcitation by the stellar UV radiation field can be important for the low-Z ions (C V, N VI, and O VII) and must be taken into account when inferring the electron density, (d) the atomic rates may not be accurate, and (e) contamination by dielectronic satellite lines (e.g., lines of O VI can be 10% of the flux of the overlapping O VII lines) and other lines. Table 1 shows the very wide range in n_e estimated for Capella's corona using different methods to correct for the continuum and background. Given the many sources of systematic error, the published errors are often underestimates. Taking all of these effects into account, Ness et al. (2002a) conclude that the electron density in Capella's corona is very close to the low density limit for O VII. They also find that for all of the stars studied, the i/f ratios for Ne IX and the higher-Z helium-like ions are at their low density limits and thus not useful for inferring coronal electron densities. The much higher densities inferred from the Fe XX–XXII lines (e.g., Mewe et al. 2001) could be due to either the high temperature emission originating in a different region of the corona than the cooler plasma seen in the O VII lines, or perhaps errors in the diagnostic techniques for the high temperature lines.

Based on the simplified quasi-static loop models of Rosner et al. (1978) and the uncertain n_e estimates, Mewe et al. (2001) proposed that (1) the cooler plasma ($T \sim 0.5 - 2$ MK) is located in large loops like solar active regions with $n_e = 10^9 - 10^{10}$ cm^{-3}, and (2) the hotter plasma ($T = 5 - 9$ MK) is located in compact loops with $n_e = 10^{12} - 10^{13}$ cm^{-3}. In Capella and especially in the more active stars described below, the cooler plasma likely refers to plasma that is not flaring, but the more variable hot plasma likely is being heated either by detectable flares or by many undetectable microflares. The much higher spectral resolution available with STIS and FUSE has been used to determine which star in the Capella system is the main emitter of X-rays and to study coronal flows and turbulence (Johnson et al. 2002).

HR 1099 (K1IV + G5IV, P = 2.84 days)

In their analysis of the coordinated Chandra/HETG, HST/STIS, EUVE, and VLA observations of HR 1099 in September 1999, Ayres et al. (2001) arrived at the following conclusions:

- The O VII, Ne IX, and Mg XI line ratios imply $n_e \leq 10^{11}$ cm^{-3}, whereas the Fe XXI line ratios formed at higher temperatures imply $n_e \leq 10^{12} - 10^{13}$ cm^{-3}. It is likely that these densities, measured at the same time, refer to different structures in the corona with plasma heated at different rates.

- The radial velocities of the Ne X 12.1 Å line follow the orbital motion of the K1 IV star, indicating that this star is the main source of X-rays from the binary. A transient ~ 60 km s^{-1} blueshift of the Ne X line, indicating upflowing hot gas, was detected before a flare seen in STIS data.

- Two flare-like brightenings were seen in emission lines formed at 10^5 K (C IV, Si IV), but were not seen in simultaneous hot Fe XXI 1354 Å line fluxes observed by STIS or in cooler Ne X lines observed by Chandra. Thus UV line brightenings, likely analogs of solar transition region explosive events, often do not have corresponding coronal flares.

- Fits to the 6–14 Å continuum observed by Chandra/LETG, imply that the Fe/H ratio in the corona of HR 1099 is 0.3 times the solar photosphere. Since the photosphere of the K1 IV star also appears to be underabundant in Fe, it is not clear whether the coronal Fe is underabundant relative to the photosphere. The high-FIP elements Ne and Ar are enhanced by factors of 10 and 25 relative to Fe. Drake et al. (2001) arrive at similar conclusions.

σ^2 CrB (F6V + G0V, P = 1.14 days)

Coordinated Chandra/HETG, EUVE, and VLA observations in June 2000 of this active RS CVn binary form the basis of the following conclusions by Osten et al. (2003):

- The 0.3–10 keV X-ray light curve with 5 minute binning was extremely stable for 0.9 days followed by a flare. This extreme stability will place severe constraints on models that attempt to explain coronal heating by microflares, although the variability has not yet been studied quantitatively.

- During a large flare, the MEG and HEG data track each other perfectly, a tribute to the calibration of the Chandra instruments. The EUV flux is delayed at the flare onset and then tracks the decay.
- To fit the fluxes of Fe lines of different ionization stages and the bremsstrahlung continuum, a range of DEMs can fit equally well. Thus the DEM is NOT unique.
- The derived values of n_e from the helium-like triplets depend on the plasma temperature and cannot be fit in a self-consistent way.
- With increasing temperature, the emitting volume decreases, n_e increases, and $P_e = n_e T_e$ increases. These trands are uncertain because they depend on the uncertain values of n_e.
- σ^2 CrB shows an inverse-FIP bias, and all of the abundances increase during the flare.

II Peg (K2–3 V–IV + ?, P = 6.7 days)

Huenemoerder et al. (2001) analyzed the Chandra/HETG observations of II Peg obtained in October 1999. They found that the DEM peaks at $\log T = 7.2$ before the flare and at $\log T = 7.6$ during the flare. The flare light curve is consistent with solar two-ribbon flare models but with a very long reconnection time of 65 ks. The coronal abundance of Fe is very low (0.1 solar photosphere), indicating an inverse-FIP bias, and the abundances increase during the flare.

Algol (B8 V + K2 IV, P = 2.8 days)

Algol is an eclipsing mass transfer spectroscopic binary system with high X-ray luminosity, $L_x = 1.4 \times 10^{31}$ ergs s^{-1}. Chandra LETG spectra revealed a bright bremsstrahlung continuum and numerous emission lines including many Fe XXI lines useful for estimating coronal electron densities. Ness et al. (2002b) and Schmitt and Ness (2002) modelled the Chandra spectra with a hot component ($T \sim 15$ MK) and a cooler component ($T \sim 8$ MK). They concluded that the hot component is primarily plasma confined in small loops at a pole of the K2IV star, because the hot lines (perhaps formed during the decay of a long duration flare) are not eclipsed in this high inclination system ($i = 81°$). Measurements of electron densities are complicated by the bright UV radiation from the B8V star that depopulates the ^3S state of the helium-like ions, especially N VI and O VII. They derive $\log n_e = 10.54 \pm 0.53$ cm^{-3} from the O VII triplet and $\log n_e < 11.5$ cm^{-3} from Fe XXI line ratios.

44i Boo (G0 V + G0 V, P = 6.4 hours)

This W UMa-type contact eclipsing binary system has an inclination $i = 73°$. The HETG spectrum of Algol shows bright emission lines but a weak continuum. In their analysis of this spectrum, Brickhouse, Dupree, and Young (2001) found that the emission measure peaks at a temperature of 5–8 MK. They also found that the X-ray emission lines are broader (~ 550 km s^{-1}) than instrumental and show orbital Doppler shifts of 180 km s^{-1} during an orbit. A large bright region at the pole of the primary star could explain the 20% quiescent modulation and the radial velocity changes.

Thus both Algol and 44i Boo show evidence for inhomogeneous coronae with brighter emission at the poles, the opposite of what is seen on the Sun.

Young Star Forming Clusters

The excellent imaging qualities of Chandra's grazing incidence telescope assembly and its two-dimensional detectors (ACIS-I and HRC-I) are providing very rich images of young star forming clusters, which in some cases include more than 1,000 sources from O stars to brown dwarfs within a single Chandra field. I list these studies in Table 2 and summarize some of their interesting results below:

Table 2. Summary of Chandra Observations of Young Clusters

Cluster	Instrument	Age (Myr)	d (pc)	Sources	$\log L_x$	Authors
Orion Nebula	HRC-I	$\sim 10^6$	470	742		Flaccomio et al. (2003a,b)
Orion Nebula	ACIS-I	$\sim 10^6$	470	1075	28.0–33.3	Feigelson et al. (2002a,b)
OMC-2, OMC-3	ACIS-I	$\sim 10^6$	~ 450	~ 400		Tsujimoto et al. (2002)
NGC 1333	ACIS I	$\sim 10^6$	318	95	28.0–31.5	Getman et al. (2002)
ρ Oph	ACIS-I	$\sim 10^6$	145	87	28.0–31.2	Imanishi et al. (2001)
M16/Eagle	ACIS-I	2×10^6	2000	1076	29.8–32.2	Gagné et al. (priv. com.)
	HRC-I					
Pleiades	ACIS-I	$\sim 10^8$	127	99	27.9–29.6	Daniel et al. (2002)
						Krishnamurthi et al. (2001)
NGC 2516	ACIS-I	$\sim 10^8$	387	82	28.7–30.6	Harnden et al. (2001)

Orion Nebula Cluster: Chandra images obtained with the HRC-I (Flaccomio et al. 2003a,b) and ACIS-I (Garmire et al. 2000, Feigelson et al. 2002a,b) show X-rays emitted by brown dwarfs, a $45M_\odot$ O star, and most stars of intermediate mass. They discovered rapid variability in the X-ray emission from an O9.5 star (θ^2 Ori A) and from some early-B stars, contrary to the predictions of radiatively accelerated wind theory. The mid-B through A stars are probably not significant X-ray sources, consistent with the results for other young clusters. A surprising result is that the strength of the X-ray emission does not depend upon the presence or absence of a circumstellar disk. The Classical T Tauri stars (CTTSs) often have $T \geq 100$ MK, even when there are no obvious flares, and both L_x and L_x/L_{bol} depend upon stellar age and mass. In their study of two star formation regions in the Orion Molecular Cloud (OMC-2 and OMC-3), Tsujimoto et al. (2002) found a trend of decreasing relative strength of the high temperature plasma emission and perhaps also a trend of decreasing coronal abundances with evolution from protostars (Class I) to T Tauri stars (Class II and III objects).

NGC 1333: Getman et al. (2002) show that in NGC 1333 the X-ray properties of young stars do not depend upon the presence or absence of disks (as indicated by the infrared K band excess) or the strength of the stellar wind. X-rays from the late-B stars in this cluster likely are emitted by their late-type binary companion stars as appears to be the case in the other clusters studied.

ρ **Ophiuchi Cluster:** In a 100 ks ACIS-I image of this young cluster, Imanishi et al. (2001a, 2002) detected 87 X-ray emitting stars, primarily CTTSs of class I (young stars with disks), II, and III (typically weak lined T Tauri stars without disks) and two brown dwarfs. None of the apparently starless cores of very young gas clouds was detected as an X-ray source, consistent with the nondetections of the evaporating gaseous globules (EGGs) in the Eagle Nebula. Both during and outside of flares, the coronal temperatures and X-ray luminosities of the class I sources are larger than for the older class II and III stars. However, the L_x/L_{bol} ratios for the older class II and III sources are typically a factor of 10 larger than for the class I sources, presumably because most of the bolometric luminosity of the class I sources is from accretion rather than the nuclear energy of the star. Flares observed from the class I sources are often extremely powerful. For example, ROSAT observed a flare on YLW 15A with a peak $L_x = 10^{33}$ ergs s^{-1}. During flares the L_x/L_{bol} ratios can far exceed the 10^{-3} value thought to characterize stars that are completely covered with active coronae. Imanishi et al. (2002) therefore proposed that the X-ray emitting regions during flares exceed the size of the star itself. Chandra detected the 6.7 keV emission line of highly ionized Fe during a flare on YLW 16A and the 6.4 keV emission from neutral Fe. Imanishi et al. (2001a) proposed that the 6.4 keV feature is due to fluorescence of neutral Fe in the disk within 20 AU of the star. The inferred coronal metal abundances of the brighter stars are typically 0.3 times those of the solar photosphere, and the coronal abundances of both low-FIP and high-FIP elements increase during flares, consistent with the idea that higher metal abundance gas from the lower atmosphere rises to fill the loops during flares.

M16, Eagle Nebula, NGC 6611: The HST WFPC2 image of the Eagle Nebula with its "Pillars of Creation" (dense molecular clouds) is arguably the most famous astronomical image obtained during the last decade. Chandra's ACIS-I observed this same field showing a large number of deeply embedded

X-ray sources in and near the "Pillars of Creation" that are spatially coincident with near-IR stellar sources seen by the ISAAC imager on the VLT. There are some 73 EGGs at the edge of the Pillars (cf. Hester et al. 1996) which are shaped by the photodissociating UV radiation field and winds from nearby massive O stars. Gagné, Mytyk, and Linsky (private communication) find that none of the X-ray sources are spatially coincident with the EGGs. This suggests that protostellar gas clouds in the EGGs have not reached an evolutionary stage where X-rays are produced.

Pleiades: Daniel, Linsky, and Gagné (2002) and Krishnamurthi et al. (2001) detected 18 out of the 23 known Pleiades members in an ACIS-I field centered on the 10^8 yr old Pleiades cluster. They detected five stars of spectral type B6–F4, but concluded that the detected X-rays are likely emitted by their cooler binary companions. Single A stars are not detected X-ray sources and thus have weak or no coronae even at age 10^8 years. The Pleiades F–M stars are variable and flares are seen from all K–M stars.

NGC 2516: This cluster is often refered to as the "southern Pleiades" because it has the same age as the Pleiades. Harnden et al. (2001) proposed that the differences between the X-ray distribution functions of the two clusters are likely due to the factor of 2 lower metal abundance of NGC 2516.

Premain Sequence (PMS) Stars

TW Hya (K7 V): Kastner et al. (2002) analyzed HETG spectra of this star, which is the nearest (56 pc) CTTS. They concluded that the observed X-rays are produced by plasma heated in an accretion column rather than in a very active solar-like corona, because (i) The DEM is sharply peaked near T = 3 MK, which is consistent with adiabatic shock heating by gas at a free-fall velocity of 150–300 km s^{-1} (similar to the observed Hα velocity), (ii) the O VII and Ne IX i/f line ratios indicate that $n_e \sim 10^{13}$ cm^{-3}, unlike coronal plasmas that generally have far lower densities, and (iii) the inferred accretion rate is consistent with observations of the C IV line flux. They find that the Ne/Fe ratio for the X-ray emitting plasma is much larger than for the solar photosphere.

Trapezium stars: Schulz et al. (2001a) detected 5 proplyds (cf. O'Dell et al. 1993) as X-ray sources, and concluded that the X-rays are emitted by embedded premain sequence stars. Schulz et al. (2001a,b) and Feigelson et al. (2002a) find that the massive Trapezium O stars are very X-ray luminous, $L_x = (2-20) \times 10^{31}$ ergs s^{-1} and hot (2–3 keV). The X-ray emission from these stars is 10 times hotter than predicted by radiatively driven stellar wind theory, but could be consistent with magnetically confined wind shocks. Kohno, Koyama, and Hamaguchi (2002) detected high temperature plasma and flares from four high-mass young stars in the Monoceros R2 molecular cloud, which they interpret as produced by magnetic activity as occurs in low-mass stars.

M Dwarfs and Brown Dwarfs

Flaring brown dwarfs: ACIS-S detected a flare on the 500 Myr old brown dwarf LP 944-20 (Rutledge et al. 2000). At flare peak $L_x = 1.2^{+0.5}_{-0.3} \times 10^{26}$ ergs s^{-1} and $L_x/L_{bol} = 2 \times 10^{-4}$. Outside of the flare $L_x < 1 \times 10^{24}$ ergs s^{-1}. Thus fully convective brown dwarfs have dynamos and at least transient coronae. Both continuous and flare X-ray emission is detected from young brown dwarfs and candidate brown dwarfs in the ρ Oph Cloud (e.g., Imanishi et al. 2001a, 2001b) with $L_x/L_{bol} = 10^{-5}$ to 10^{-3}.

YY Gem (dM1e + dM1e, P = 0.81 days): Stelzer et al. (2002) reported on coordinated Chandra/LETG and XMM-Newton observations of the eclipsing binary YY Gem observed in September 2000. YY Gem is an active flaring system with $L_x = (2-8) \times 10^{29}$ ergs s^{-1}. The Chandra and XMM fluxes are consistent with each other, demonstrating the excellent flux calibration of both instruments. Of the helium-like ions, only the O VII triplet has adequate S/N for analysis. Ness et al. (2002a) find that the i/f ratio implies a coronal density $n_e \approx 2.5 \times 10^{10}$ cm^{-3} at a temperature of T = 2–3 MK. The coronal abundances are subsolar, and Fe increased during a flare.

AD Leo (M3.5V): Brown et al. (private communication) are analyzing the mostly "quiescent" emission observed with the Chandra HETG. The coronal abundances show an inverse-FIP bias with the low-FIP elements underabundant and the high–FIP element Ne overabundant. The abundances relative to H are difficult to measure as the X-ray continuum is weak.

AU Mic (dM1e): Brown et al. are also analyzing the Chandra HETG spectrum of this flare star. The X-ray emission is mostly "quiescent" emission with $L_x = 5.5 \times 10^{29}$ ergs s^{-1} and $L_x/L_{bol} = 2.2 \times 10^{-3}$. The coronal abundances show an inverse-FIP bias like AD Leo.

Solar-type Stars

I know of only one coronal model derived from analysis of a Chandra spectrum of an F-, G-, or K-type star located on or near the main sequence. Raassen et al. (2002) analyzed a 70.4 ks Chandra LETG spectrum and a 90.5 ks XMM-Newton spectrum of Procyon (F5 IV-V). This slightly evolved, slowly rotating star is about 1.7 times the solar mass and has an X-ray luminosity $\log L_x = 28.4$, which is moderately larger than the Sun at solar maximum, $\log L_x = 27.67$ (Peres et al. 2000). Analyzing this spectrum with multi-temperature models using the SPEX software package, Raassen et al. (2002) find that most of the emission measure is at temperatures between 1 and 3 MK like the Sun with no significant amount of plasma at temperatures above 4 MK. One difference from the Sun is that the coronal abundances do not show a FIP bias, but are consistent with solar photospheric abundances.

Ness et al. (2001, 2002a) derived the coronal densities of Procyon, α Cen A and B, ϵ Eri, AD Leo, YY Gem, and the binaries Algol, Capella, UX Ari, and HR 1099 from the helium-like triplets. In all cases they could not infer reliable coronal electron densities from the higher-Z ions (Ne IX, Mg XI, and Si XIII) as the i/f line ratios are consistent with the low density limits. The O VII i/f ratios indicate coronal densities in the range 1–3$\times 10^{10}$ cm^{-3} for Procyon, ϵ Eri, YY Gem, Algol, and HR 1099. For the inactive stars (e.g., α Cen A and B), the O VII i/f ratio is at the low density limit and thus is not a useful diagnostic.

Wargelin and Drake (2001, 2002) proposed that the mass loss rates for solar-type dwarf stars could be estimated from the X-rays produced when stellar wind ions charge exchange with neutral hydrogen in the hydrogen walls around the stars. This is a difficult measurement because the charge-exchange X-ray emission is much fainter than the stellar coronal emission. They searched for this emission around the M dwarf star Proxima Centauri, obtaining an upper limit of 8.6 times the solar mass loss rate. Their method is much less sensitive than the H I Lyman-α line absorption technique developed by Wood et al. (2002), but the Wargelin and Drake method is complementary and may be usefully applied to other stars.

Hot Stars

Chandra has obtained spectra of a number of bright O-type stars including ζ Puppis (O4f), θ^1 Orionis C (O6pe), δ Orionis A (O9.5 II), ζ Orionis (O9.7 Ib), and the Wolf-Rayet binary systems WR 147 and γ^2 Velorum. The spectral resolution of the HETG is sufficient to resolve the shapes of the bright emission lines. Except for δ Orionis A, the emission lines are broad, blueshifted, and in some cases skewed, providing direct evidence that they are formed in an accelerating stellar wind with terminal velocities as large as 2000 km s^{-1}. The presence of Fe XXIV and Fe XXV lines in the spectrum of θ^1 Orionis C (Schulz et al. 2001b) and other stars indicates very hot plasma ($\log T = 7.8$), which is not predicted by simple wind shock models and may be formed in a magnetic corona. Analysis of the helium-like ion triplet lines, including photoexcitation processes, can determine the electron densities where the emission lines are formed (e.g., Waldron and Cassinelli 2001). The X-ray lines in the Wolf-Rayet binary WR 147 are formed where the winds of the two stars collide (Pittard et al. 2002).

Stars without Coronae

Arcturus (K1 III): Despite a deep (18.4 ks) HRC-I image, Arcturus is the brightest nearby star with no evidence for X-ray emission. Ayres et al. (2003) used the HRC-I detector for this observation because it has no red leak that could compromise an X-ray detection. The HRC-I image shows no photons at the position of Arcturus, corresponding to a 3σ count rate $\leq 2.3 \times 10^{-4}$ counts s^{-1} for the 0.2–2 keV energy interval. Thus $\log L_x \leq 25.3$ (3σ) and $L_x/L_{bol} \leq 10^{-10}$ (3σ). The X-ray surface flux is therefore $\leq 1/40{,}000$ times solar. Since emission lines of C IV and Si IV formed at 10^5 K are seen in UV spectra of Arcturus, either the maximum atmosphere temperature is $\leq 10^5$ K, or as proposed by Ayres et al. (private communication), the hot corona is buried beneath cool material.

WHAT HAVE WE LEARNED ABOUT STELLAR CORONAE?

What types of stars do not have coronae? Even very young stars of late-B to early-A spectral type either do not have coronae or their coronae are very weak. Also, late-K and M giants and supergiants either do not have coronae or their coronae are smothered by overlying cool gas.

How are coronae heated? Magnetic fields generally play a critical role either through reconnection events, MHD wave dissipation, or magnetic shocks in O stars. Accretion shocks in the magnetic funnels may heat the coronae of PMS stars.

What are coronal temperatures? For active stars T can be $\geq 10^8$ K, even at times when there are no large flares. Coronal plasmas at temperatures of several times 10^7 K are commonly observed.

What do the inferred electron densities mean? Measurements of weak emission lines (essential for inferring n_e from line ratios) are difficult because of uncertain corrections for the continuum, scattered light, and blends. Electron densities are uncertain because the diagnostic line ratios are often close to their low density limits and uncertainties in the atomic rates. Even worse – the inferred electron densities are EM weighted, and thus are not representative of a corona as a whole.

What are typical geometries? The usual assumption based on solar analogy is that the hot plasma is confined in static magnetic loops, but solar observations dispute this. Rapidly rotating active stars have inhomogeneous coronae (e.g., extra emission near the poles of 44i Boo and Algol). X-ray flux monitoring during eclipses and Doppler shifts seen in high resolution UV and FUV spectra of the Fe XXI 1354 Å and Fe XVIII 977 Å emission lines are the best ways to study stellar coronal structure.

When in the lifetime of a star do coronae begin? Somewhere in Class 0. EGGs in the Eagle nebula are not detected X-ray sources, but some proplyds in the Orion Nebula contain PMS stars that have hot coronae and are X-ray sources.

Do coronal and photospheric abundances differ and why do they differ? Very active stars show inverse-FIP coronal abundances and moderately active stars (e.g., Capella) show no clear trend relative to the solar photosphere. However, for many stars there are no accurate photospheric abundances. There is no theory with predictive power that we can confidently use to explain the observed inverse-FIP abundances, in particular the high Ne and low Fe abundances of the very active stars.

General Assessment: Chandra is an excellent observatory producing truely beautiful data. To take full advantage of this unique resource, we need more trained X-ray astronomers, both theoreticians and observers. Analysis of the Chandra data brings into focus its limitations, and we look forward to higher spectral resolution, higher throughput, and ultrahigh angular resolution in future X-ray missions.

ACKNOWLEDGEMENTS

This work is supported by NASA grant H-04630D to NIST and the University of Colorado. I would like to thank my colleagues Tom Ayres, Alec Brown, Rachel Osten, Seth Redfield, and Brian Wood at the University of Colorado for discussions on many aspects of this paper. I also thank Marc Gagné and Anna Mytyk at West Chester University for permission to cite results for M16 prior to publication.

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Received: 4 December 2002; Accepted: 6 February 2003.