Stellar Coronae in the Chandra and XMM-Newton Era
ASP Conference Series, Vol. TBD, 2001
F. Favata & J. Drake

Historical Perspective — Lessons Learned and Lessons to be Learned

Jeffrey L. Linsky

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

Abstract. Chandra and XMM-Newton are obtaining critically important observations needed to answer long standing questions about the physical processes occuring in stellar coronae. In my historical perspective of stellar coronal observations and models, I will emphasize our inadequate understanding of the essential atomic and plasma physics and MHD processes that underlie the complex phenomena revealed by Chandra and XMM-Newton and their preceding X-ray observatories. Close up observations of the solar corona challenge our simple models for stellar coronae, but the Sun may not be a good guide for the more extreme phenomena revealed by the stellar X-ray observations.

"The past is never dead. It's not even past." *William Faulkner*

At this meeting on Stellar Coronae in the Chandra and XMM-Newton Era, we will be discussing the new data provided by the powerful new satellites and the new insights concerning the physical processes operating in stellar coronae that are stimulated by analysis of these data. While we are enjoying this astrophysical feast, we should keep in mind that the major questions concerning stellar coronae have been with us for some time. Prior to the completely new X-ray spectra and the deeper and far higher resolution images provided by Chandra and XMM-Newton, we had only partial answers to some of these questions and crude models for stellar coronae. Faulkner was right, although he likely would not understand anything that we will say at this meeting. The past should be very much with us: we shall therefore build upon what has proceeded us rather than reinventing what already exists. Historical perspective can be very useful.

Since it is impossible in a short time to present a comprehensive review of stellar coronae, I will try to give a perspective, emphasizing what has been learned and what remains to be learned. Of necessity I must simplify, so I have arbitrarily divided the history of the field into five distinct periods that I call for convenience the Stone Age, Bronze Age, Silver Age, Golden Age, and Diamond Age.

1. The Stone Age – First Observations and Untested Theories

Optical observations of the first known corona, that of the Sun, during total eclipses predate written records. By the 1950s the solar corona had been observed optically, in the UV, and at radio wavelengths. The solar corona was known to be hot and extended above the photosphere by analysis of the optical forbidden lines of Fe X and Fe XIV and the radio spectrum. The first X-ray observations began with crude sounding rocket instruments in the 1950s (see Vaiana, Krieger, & Timothy 1973 for a review), but in 1973 instruments on Skylab/ATM provided the first high quality X-ray images and both X-ray and XUV spectra of the solar corona. Some of the major accomplishments of the Skylab/ATM mission (see review by Golub and Pasachoff (1997)) include studies of the close spatial connection between the bright X-ray emission and magnetic active regions, the evolution of coronal holes (regions of low X-ray emission where the magnetic field lines are open and the fast solar wind originates), the correlation of coronal bright points with small emerging magnetic bipoles, and the rapid evolution of X-ray bright active regions in response to changes in the coronal magnetic field structure as the field lines reconnect. How reconnection can occur on rapid time scales is a mystery that is still with us.

The first X-ray detection of a star other than the Sun was serendipitous. In an April 1974 sounding rocket experiment to search for X-ray emission from Sirius, Catura, Acton, & Johnson (1975) observed Capella for 1.2 second to calibrate the attitude control system. In this very short time, they detected a signal of 18 X-ray photons. During the 1970s, the Copernicus, ANS, and Ariel V satellites detected X-rays from a few dMe and RS CVn binary stars during very luminous flares (see Linsky 1991 for a review). The A-1 and A-2 instruments on HEAO-1 (Aug 1977 to Jan 1979) also detected bright flares. The A-2 low-energy X-ray sky survey instrument detected quiescent emission from a limited number of X-ray bright late-type stars. The list includes six G and K dwarfs localted within 10 pc (Walter *et al.* 1980a) and 15 RS CVn binary systems (Walter *et al.* 1980b). The G and K dwarfs were detected with $L_x/L_{bol} \approx 10^{-4}$ and $L_x = (1-4) \times 10^{-29}$ erg s^{-1}, which is roughly the X-ray emission that one would predict if the star were completely covered with solar-like active regions. The coronae of the RS CVn systems are far more luminous ($L_x = (3-40) \times 10^{30}$ erg s^{-1}), 4 to 5 orders of magnitude larger than for the Sun.

By the end of the 1970s with the publication of the stellar coronae detection of HEAO-1, the observational and theoretical limitations of the field were recognized. The observational limitations included:

- Low sensitivity $\Rightarrow$ detection of only the brightest X-ray sources. It was widely appreciated at the time that the HEAO-1 detections were likely the "tip of the iceberg" with many more detections awaiting more sensitive instruments. The absence of volume limited or even deep flux limited surveys meant that one did not know which classes of stars are X-ray sources or how L_x depends upon stellar parameters.

- Low angular resolution $\Rightarrow$ inability to study interesting crowded fields (e.g., clusters where young stars reside) and to separate binaries (e.g., Sirius A/B). Large error boxes led to uncertain identifications.

- Low energy resolution meant that one could compare the data only with the simplest one-component thermal models. Measurements of coronal abundances would have to wait for new instruments.

At the same time coronal modelling could be summarized as follows:

- Stellar coronal models generally followed solar analogy. The extremely large X-ray luminosities of the RS CVn systems severely challenged efforts to simply scale up solar models.

- Two types of models were discussed: isothermal coronae in hydrostatic equilibrium, and isothermal loops in hydrostatic equilibrium following Rosner, Tucker, & Vaiana (1978). For RTV-type models the huge X-ray luminosities of the RS CVn systems either required very high pressures (which could not be tested without independent measurements of electron density that required spectroscopy) or loops that completely fill a very extended corona.

- Coronal heating was assumed to result from the dissipation of acoustic or magneto-acoustic waves generated in the convection zone. Thus, according to this assumption, stars without convective zones cannot have coronae. Future observations of luminous X-ray emission from O stars would invalidate this assumption.

- The correlation of strong X-ray emission from solar active regions with strong magnetic fields was not incorporated into most theoretical models of stellar coronae.

- Theoretical models and observations did not come together. In particular, the large range of X-ray luminosities for stars with the same convective zone parameters was not appreciated or satisfactorily explained.

2. The Bronze Age – Results from Einstein and EXOSAT and a New Generation of Models

The next two X-ray satellites greatly expanded our understanding of stellar coronae. HEAO-2 (better known as the Einstein X-ray Observatory) operated from November 1978 to April 1981. Its Imaging Proportional Counter (IPC) and High Resolution Imager (HRI) instruments provided images with a few arc-second resolution and the Solid State Spectrometer (SSS) provided the first low resolution spectroscopy ($\Delta E(eV) \approx E/160$). EXOSAT operated from May 1983 to Apr 1986. It contained Low Energy (LE) and Medium Energy (ME) detectors that supported observations through filters and transmission gratings and a Gas Scintillation Proportional Counter (GSPC). The very thoughtful review paper by Rosner, Golub, & Vaiana (1985) summarized the essential findings of this period. Since 16 years later their observational conclusions are still mostly valid, I quote from what they said:

Which Stars have Coronae? "The data are consistent with all dwarf stars of spectral type dF through dM being X-ray emitters with quiescent luminosities ranging between roughly 10^{26} and 10^{31} erg s^{-1}."

Hot Stars: "All stars earlier than (roughly) B5 are X-ray emitters at emission levels between 10^{29} and 10^{34} erg s^{-1} and with a roughly constant $L_x/L_{bol} \sim 10^{-7}$ independent of luminosity class."

Warm Stars: "There is a narrow spectral range – from roughly B8 to A5 – on the main sequence for which there is no credible evidence for any X-ray emission from spectroscopically normal and Am stars, but there is evidence for X-ray emission from Ap stars."

Cool Giants: "Late spectral type giants and supergiants experience a cutoff in X-ray emission levels as one moves to later spectral types."

PMS Stars: "Pre-main-sequence stars are very vigorous X-ray sources and show a definite trend of decreasing mean emission levels with nominal stellar age."

Coronal Temperatures: "The X-ray spectra of late-type stars are thermal, with single component temperatures ranging between 10^6 and several times 10^7 K; however, there is considerable evidence that a **single-component analysis is not an adequate description of spectra** [my emphasis] for sources with sufficient count statistics."

Flares: "As would be expected from Sun-like activity behavior, late spectral type main sequence stars and evolved stars in close binary systems (e.g., RS CVns) show episodic highly transient behavior in X-rays."

Close Binaries: "X-ray emission levels from close binary systems, such as RS CVn and W UMa stars, in which accretion is not thought to play a major role, are substantially enhanced over those from effectively single stars, whose classical stellar characteristics are similar to those of the individual binary components."

The physical description of coronal plasmas in the Rosner *et al.* (1985) review paper left a number of unanswered questions. The text in italics are my comments on their conclusions.

Insight from Skylab/ATM: These observations of the solar corona demonstrated the close connection of magnetic fields (extrapolated up from the photosphere) and bright X-ray emission. Therefore magnetic fields play a central role in coronal X-ray emission.

Magnetic Flux Tube Models: The models of Rosner, Tucker, & Vaiana (1978) and refinements that include flows along the field lines and loop heights greater than a pressure scale height assume that most or all of the X-ray emission comes from hot plasma confined in magnetic flux tubes:

- Magnetic fields heat the plasma, *but a physically self-consistent detailed model is needed to describe the heating and to predict its dependence on stellar parameters accurately.*
- Magnetic fields confine the high pressure plasma, thereby preventing energy loss by an expanding wind.
- Magnetic fields thermally isolate the plasma from cooler surroundings.

- Magnetic fields guide thermal conduction down into the transition region thereby heating the cooler plasma.
- The solar corona can be modelled by a statistical mix of loops with different physical properties (size scale, mean field strength, mean plasma temperature and pressure). *Thus one component stellar coronal models cannot be valid, even if they fit the available data.*

Limitations of the Models: Coronal models proposed in the 1970s and most models today still do not adequately explain:

- Rapid variability of the emission from loops.
- Rapid reconnection events and continuous magnetic topological change of the coronal magnetic field driven by emerging magnetic fields in the photosphere.
- Topological disconnections between coronal and transition region loops. *Thus correlations between properties of X-ray emitting and cooler plasmas are statistical not physical.*

A Central Issue: To what extent is extrapolation from solar coronal models justified? The real test is for stars very different from the Sun (O stars, PMS stars, cool giants, low mass stars, etc.). How far can solar analog be pushed?

- O star coronae are not solar-like, but are heated by shocks in radiatively driven winds (cf. Lamers & Cassinelli 1999). *Can this model explain nonthermal radio emission and the very hot temperatures of X-ray emission?*
- For F–M stars there is a general correlation of L_x with rotation ($L_x \sim (vsini)^2$) (e.g., Pallavicini, *et al.* 1981) as expected if an $\alpha\Omega$-type dynamo controls the magnetic flux in the corona. *Observations of young stars in clusters that have saturated L_x at high rotation rates challenge this simple explanation*
- PMS stars are luminous variable X-ray sources ($L_x(PMS) \sim 1000 \times L_x$(ordinary stars). *Can this be explained simply as solar-like activity of a rapidly rotating star, or do they need another energy source – interacting stellar and disk magnetic fields with shear from disk rotation or accretion?*

3. The Silver Age – Results from ROSAT, ASCA, Beppo-SAX, and EUVE

This era began with the launch of ROSAT in June 1990, which operated until February 1999. ASCA operated between February 1993 and July 2000, and Beppo-SAX was launched in April 1996 and is still operating. EUVE was launched in June 1992 and operated until shut down in January 2001. This satellite differed from the other X-ray satellites in that it obtained spectra in the 70–760 Å range and broad-band EUV images.

All-sky Surveys: ROSAT obtained the first soft X-ray flux limited all-sky survey. In the survey 145,060 sources were detected, including 18,811 bright sources (Voges *et al.* 1999). There are now flux limited and volume limited catalogs of nearby stars, giant stars, and different classes of stars. A total of 1252 nearby stars were detected including "virtually every late-type star with spectral type later than A7" (Hünsch *et al.* 1999). EUVE detected 734 sources in its surveys and pointed observations of which 24 are early-type stars and 275 are F–M stars (Bowyer *et al.* 1996).

Clusters: Deep surveys of stars in many star-forming clusters like Orion and somewhat older clusters like the Pleiades, Hyades, and α Per, are among the major accomplishments of the ROSAT observing program. Feigelson & Montmerle (1999) have summarized these observational studies and discuss rotation-activity, age-activity, disk-braking, and other aspects of young star evolution.

Brown Dwarfs: The first detection of X-rays from a brown dwarf (BD) was by Neuhäuser & Comerón (1998), who detected a BD in the Chamaeleon I Dark Cloud. Subsequent papers showed that X-ray emission from BDs decrease rapidly with age.

Abundances: Despite their modest energy resolution, EUVE and ASCA data provided the first indications of stellar coronal abundances. In active stars metals with first ionization potentials (FIP) < 10 eV, for example Fe, are underabundant instead of overabundant as in the solar corona and wind. Examples are the studies of the RS CVn systems UX Ari (Güdel *et al.* 1999) and σ^2 CrB (Osten *et al.* 2000). More detailed studies of the anti-FIP effect require the spectral resolution of Chandra and XMM-Newton and theoretical investigations of element separation and diffusion physics.

Flares: BeppoSAX provided evidence for extremely hot plasmas during stellar flares. Temperatures of 10^8 K or higher were detected at the peak of giant flares on Algol (Favata & Schmitt 1999) and on AB Dor (Maggio *et al.* 2000). Two and three temperature component models were constructed to explain the flare emission.

K Giants: Hybrid-chromosphere stars (e.g., α TrA) are X-ray sources, but old K giants (e.g., Arcturus and Aldebaran) are not as demonstrated by very low flux upper limits (e.g., Reimers *et al.* 1996; Hünsch *et al.* 1996)

Sun as a Star: The Sun is very close to the bottom of stellar activity as measured by X-ray surface flux and L_x.

Status of Models: Most models compute the X-ray emission from an ensemble of flux tubes with one or two temperatures, but these models include no dynamics and no heating rates that are predicted by theory.

4. The Golden Age – X-ray spectroscopy and the challenge of TRACE

At this conference we will learn of the exciting observations obtained with Chandra and XMM-Newton and models to explain the data, but it is important to ask whether the models are sufficiently realistic. What is the Sun telling us? The Transition Region and Corona Explorer (TRACE), which images the Sun in lines of Fe XII to Fe XV, has been providing very detailed information on the anatomy of a real star – the Sun. For a summary of the major results from the TRACE satellite I refer the reader to Schrijver *et al.* (1999) and papers and talks by Alan Title, for example his Hale Prize Lecture at the Pasadena AAS meeting (June 7, 2001). Here is my list of some of the major discoveries obtained from the analysis of TRACE data:

Hyperactive Magnetic Field: Fifty active regions emerge in the photosphere every day and the photospheric magnetic field is replaced every day. Thus a typical emerging bipole brings 10^{19} Maxwells of magnetic flux into the corona.

Energy Input: 25% of the kinetic energy of convection in the photosphere generates magnetic fields. Thus an enormous amount of magnetic energy continually buffets the coronal magnetic field.

Filamentary Structure: Coronal magnetic field loop structures are much smaller than present resolution. Thus even at highest spatial resolution, spectrographs will observe a mixture of plasma temperatures.

Inhomogeneity: Coronal loops are not uniformly heated and are not steady state. Thus homogeneous, steady state models lack essential physics and should not be trusted.

Reconnection: The coronal magnetic field is reconnecting to form new structures all the time. Reconnection occurs many orders of magnetude faster than predicted by classical MHD theory. Thus we need to model the magnetic field with 3-D MHD on very small scales with nonclassical resistivity.

Scaling: Energy input to the corona occurs at very small scales (microflaring) and leaves in much larger scales (photon mean free paths, CMEs, etc.). Thus the energy equation must include transfer processes on a very wide range of scales.

Nonthermal Phenomena: Electron beams impacting the lower atmosphere during flares produce the observed bright points. thus nonthermal phenomena are an essential part of flares and perhaps all of coronal heating processes.

Here is the challenge that stellar coronal physicists: Can future models of stellar coronae include the essential physics clearly indicated by the observations of the Sun by TRACE?

5. The Diamond Age – High resolution X-ray spectroscopy and imaging

What critical coronal science lies beyond the capabilities of Chandra and XMM-Newton? Here are some questions that should be address by the next generation of X-ray observatories:

Very Faint Coronae: Do those classes of stars for which no X-rays have been detected so far (e.g., K-M giants, nonflaring old brown dwarfs, late B-early A stars) have very low coronal emission measures or no hot plasma? *Answering this question requires more sensitivity.*

Geometry: What are the important structures in a stellar corona? How extended are coronae? Are the structures magnetically confined? Is there hot plasma between binary stars where magnetic fields interact? *Answering this question requires high resolution imaging.*

Nonthermal Plasma: What types of stars emit hard ($E > 10$ keV) X-rays? Do hard X-rays imply nonthermal or very hot electrons? Why are gyrosynchrotron radio and thermal bremsstrahlung X-ray emission correlated? *Answering this question requires sensitive hard X-ray imaging and spectroscopy.*

Abundances: Is the inverse-FIP effect real? Why are low FIP metal abundances depleted, and why do they rise to photospheric values during flares? *Answering this question requires improved atomic physics and plasma physics of diffusion and fractionation.*

Ionization: How valid is the assumption of ionization equilibrium during flares and outside of flares? *Answering this question requires more sensitivity.*

Flares: What is a self-consistent physical model for flares that has predictive power? *Answering this question requires higher spectral resolution to study dynamics and coordinated X-ray/UV/optical/radio observations.*

Dynamics: What flows occur in stellar coronae? How much energy is transported by the flows? Does only the coolest coronal plasma expand as a wind? *Answering this question requires high resolution spectroscopy.*

Energy Source: What mechanism(s) provide energy (thermal, kinetic, nonthermal particles) into a corona? *Answering this question requires high resolution imaging and spectroscopy.*

Let's make Con-X, Zeus, MAXIM, and future high resolution spectroscopy missions happen, and include in stellar coronal models the essential physics that we know is critically important for the solar corona.

Acknowledgments. I wish to thank the people with whom I have had discussions concerning stellar coronae. These include Tom Ayres, Alec Brown, Graham Harper, Rachel Osten, and Steve Skinner at CASA/University of Colorado; Greg Herczeg, Seth Redfield, and Brian Wood at JILA/University of Colorado; and Marc Gagné at West Chester University. This work is supported by NASA through grant H-04630D to NIST and the University of Colorado.

References

Bowyer, S., Lampton, M., Lewis, J., Wu, X., Jelinsky, P., & Malina, R.F. 1996, ApJS, 102, 129

Catura, R.C., Acton, L.W., & Johnson, H.M. 1975, ApJ, 196, L47.

Favata, F. & Schmitt, J.H.M.M. 1999, A&A, 350, 900

Feigelson, E.D. & Montmerle, T. 1999, ARA&A, 37, 363

Golub, L., & Pasachoff, J.M. 1997, The Solar Corona (Cambridge University Press: Cambridge)

Güdel, M., Linsky, J.L., Brown, A., & Nagasi, F. ApJ, 511, 405

Hünsch, M., Schmitt, J.H.M.M., Schroeder, K.-P., & Reimers, D. 1996, A&A, 310, 801

Hünsch, M., Schmitt, J.H.M.M., Sterzik, M.F., & Voges, W. 1999, A&AS, 135, 319

Lamers, J.G.L.M. & Cassinelli, J.P. 1999, Introduction to Stellar Winds (Cambridge University Press: Cambridge)

Linsky, J.L. 1991, Mem. S. Ast. It., 62, 307

Maggio, A., Pallavicini, R., Reale, F., & Tagliaferri, G. 2000, A&A, 356, 627

Neuhäuser, R. & Comerón, F. 1998, Science, 282, 83

Osten, R.A., Brown, A., Ayres, T.R., Linsky, J.L., Drake, S.A., Gagné, M., & Stern, R.A. 2000, ApJ, 544, 953

Pallavicini, R.P., Golub, L., Rosner, R., Vaiana, G.S., Ayres, T., & Linsky, J.L. 1981, ApJ, 248, 279

Reimers, D., Hünsch, M., Schmitt, J.H.M.M., & Toussaint, F. 1996, A&A, 310, 813

Rosner, R., Tucker, W.H., & Vaiana, G.S. 1978, ApJ, 220, 643

Rosner, R., Golub, L., & Vaiana, G.S. 1985, ARA&A, 23, 413

Schrijver, *et al.* 1999, Solar Phys., 187, 261

Vaiana, G.S., Krieger, A.S., & Timothy, A.F. 1973, Solar Phys., 32, 81

Voges, W., *et al.* 1999, A&A, 349, 389

Walter, F.M., Bowyer, S., Linsky, J.L., & Garmire, G. 1980b, ApJ, 236, L137

Walter, F.M., Cash, W., Charles, P.A., & Bowyer, C.S. 1980a, ApJ, 236, 212