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Plasma Motion and Kinematics in Cool and Hot Stars

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Abstract The environments of both hot and cool stars are the sites of highly dynamic processes involving motion of gas and plasma in winds, flows across shocks, plasma motions in closed magnetic fields, or streams along magnetospheric accretion funnels. X-ray spectroscopy has opened new windows toward the study of these processes. Kinematics are evident in line shifts and line broadening, and also more indirectly through the analysis and interpretation of density-sensitive lines. In hot stellar winds, expanding-wind kinematics are directly seen in broadened lines although the broadening has turned out to often be smaller than anticipated, and some lines are so narrow that coronal models have been revived. Although X-ray spectra of cool stars have shown line shifts and broadening due to the kinematics of the entire corona, e.g., in binary systems, intrinsic mass motions are challenging to observe at the presently available resolution. Much indirect evidence for mass motion in magnetic coronae is nevertheless available. And finally, spectral diagnostics has also led to a new picture of X-ray production in accreting pre-main sequence stars where massive accretion flows collide with the photospheric gas, producing shocks in which gas is heated to high temperatures. We summarize evidence for the above mechanisms based on spectroscopic data from XMM-Newton and Chandra.

Keywords X-rays: stars · Stars: early-type · Stars: late-type · Stars: pre-main sequence

1 Introduction

High-resolution X-ray spectroscopy has paved the way to the study of kinematics and plasma motion in stars and their environments. Subtle line shifts and line broadening are indicative

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of line-of-sight motions of X-ray emitting plasma, and entire line profiles may provide insight into velocity fields combined with absorbing gas.

Such spectral features have various origins. The simplest is the motion of a star itself, in our cases specifically the motion of a binary component around the center of mass. Line centroid shifts can easily be measured if the velocity at quadrature reaches at least a few tens of km s^{-1} for bright X-ray sources. In exceptional cases, the location of the X-ray source (or rather, its centroid) with respect to the star itself can be determined. A number of stellar systems provide such information, in particular binaries of the RS CVn and Algol type, or close binaries consisting of two main-sequence stars.

Rotation provides another source of motion. While a spherically symmetric atmosphere around a rotating star will result in broadened lines, periodic line-centroid shifts have given evidence for structured coronae in cool stars. Extracting Doppler information from rotation, however, gives a highly biased view of stellar atmospheres: only the most extreme, rapid rotators, among them very young, single stars or evolved FK Com-type giants, produce enough Doppler shift to make such analysis meaningful. Average, more moderately rotating stars remain inaccessible to this method.

Beyond pure kinematics, many stellar systems also reveal evidence for physically induced mass motions in their extended atmospheres and environments. Stellar winds are among the best-studied plasma flows in stars, but so far such studies are confined to early-type, massive stars as the tenuous, ionized hot winds around cool stars like the Sun are presently still inaccessible to X-ray spectroscopy (and other detection methods; a different type of cool winds, those from T Tauri stars, can be well detected in the ultraviolet or at radio wavelengths). Line profiles in X-ray spectra from hot stars deliver important parameters for models describing both the radial wind velocity and the density profiles.

In atmospheres of cool stars, mass motions are guided by magnetic fields. Evaporative flows during flares are important examples. They provide insight into the magnetic energy release processes and magnetic confinement. Here, the analogy with the solar corona has been crucial for most modeling efforts.

In recent years, evidence for mass motions and their signatures in X-ray spectra has also emerged from accreting pre-main sequence stars. Here, shock formation and interactions of the accreting material with the coronal/magnetospheric environment of the star appear to be fundamental. Spectroscopic observations thus help to delimit mass accretion rates and the impact geometry on the stellar surface. Analogously, some outflows and jets also produce X-rays, providing information on shock velocities, densities and pressures within the jet.

The following sections summarize evidence for mass flows and information from kinematic studies based on high-resolution spectroscopy from XMM-Newton and Chandra. We discuss evidence in cool stars, accreting pre-main sequence stars, and winds of hot stars. For a more detailed view, we refer the reader to Güdel and Nazé (2009).

2 Cool Stars: Kinematics and Plasma Motion

2.1 Rotation and Orbital Motion

In exceptional cases, stellar rotation or orbital motion in binaries is sufficiently high to induce shifts or broadening of coronal X-ray lines. This information can in principle be used to image the 3D structure of coronal features, i.e., their extent, height, and location on the star. So far, only rough estimates for these parameters are possible given that maximum velocities are close to the velocity resolution of present-day spectrometers, and detailed line

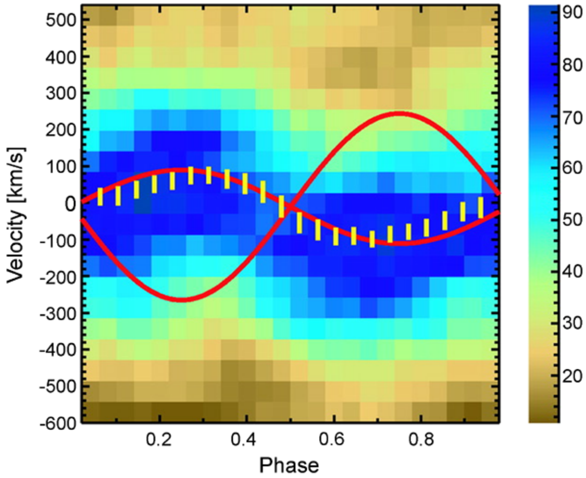

Fig. 1 Composite line profiles (vertical direction) for the contact binary VW Cep, as a function of orbital phase (horizontal direction). Highest flux is indicated in *dark blue* (see *bar to the right*). Several lines of iron and Ly lines of oxygen have been co-added. *Yellow bars* indicate the 90% confidence limits of the centroid position of the composite line. The *red sinusoidal lines* indicate the center-of-mass velocities of the binary components (from Huenemoerder et al. 2006, reproduced by permission of the AAS)

profiles cannot yet be recorded. The vast majority of coronal stars cannot yet be mapped using such kinematic information.

At the most basic level, velocity (centroid) information indicates which component in a binary dominates the X-ray emission. Examples include the RS CVn-type binary HR 1099 in which line shifts clearly follow the active subgiant rather than the much smaller main-sequence star (Ayres et al. 2001), the RS CVn binary AR Lac in which both components contribute (Huenemoerder et al. 2003), and the M-dwarf binary YY Gem in which line broadening together with X-ray eclipses indicates that both nearly identical stars are similarly active (Güdel et al. 2001).

In a few cases, further details on the source location can be derived. Brickhouse et al. (2001) and Huenemoerder et al. (2006) reported periodic line shifts up to 100–200 km s^{-1} in phase with the orbital motion in the contact binaries 44i Boo and VW Cep, respectively (Fig. 1). In both cases, the primary dominates the X-ray output, with sources in 44i Boo being located close to one of the poles of the star.

In the case of Algol, line shifts and broadening together support the view that X-rays originate entirely on the K-type secondary while the B-type binary is X-ray dark (Chung et al. 2004). A small disagreement between line shift measurements and the predicted orbital velocity of the K star suggests that the center of the coronal emission is slightly displaced toward the center of gravity, an effect probably related to the tidal deformation of the K star in this close binary system.

Only a few rapidly rotating stars have been successfully studied using X-ray Doppler information. Periodic line shifts together with light curve modulation in the young K star AB Dor support a model consisting of a low-lying, $\lesssim 0.5R_*$ distributed corona and several compact, $\lesssim 0.3R_*$ active regions (Hussain et al. 2005). FK Com-type rapidly rotating giants with surface velocities >100 km s^{-1} are ideal to exploit rotational motion in X-rays. Line broadening in YY Men at levels of 100–200 km s^{-1} could indicate a coronal source confined to about one pressure scale height or $\approx 3R_*$ above the equator, but the extremely high coronal temperatures around 40 MK make Doppler thermal broadening equally important (Audard et al. 2004). Near-polar X-ray sources confined to a height of $\approx 1R_*$ are indicated in the prototype FK Com, based on line shifts, line broadening, and comparison with surface Doppler images (Drake et al. 2008).

2.2 Plasma Flows in Coronal Magnetic Fields

The Sun shows a bewildering variety of plasma motions across all atmospheric layers from the photosphere to the outer corona (e.g., oscillations within coronal loops, loop motions, chromospheric up- and downflows, coronal flows and mass ejections), and of course in the solar wind. In the corona, mass motions are guided by closed magnetic fields. There is presently little hope to find similarly rich evidence in magnetically active stars given the lack of spatial resolution; indirect evidence for coronal mass motions is at least available from stellar flares.

Coronal flares in active stars are the analogs of solar coronal events. Flares explosively release magnetic energy in the course of a magnetic instability most likely to involve magnetic reconnection. Energy is transformed to heat (by Ohmic dissipation), mass motion in the reconnection region, and—perhaps most importantly—in kinetic energy of highly accelerated particles. The latter are trapped in coronal magnetic fields, traveling from the coronal acceleration region downward toward the magnetic-loop footpoints in the chromosphere. Electrons with high pitch angles remain trapped in the loops, evidenced by their gyrosynchrotron emission. Low-pitch angle electrons and ions will propagate into chromospheric layers where they deposit their energy; this process is evident in UV and "white-light" excess emission from chromospheric and photospheric heating, as well as in prompt non-thermal hard X-rays and gamma-rays from thick-target collisions. As a consequence of rapid heating up to $> 10^7$ K, chromospheric plasma escapes ("evaporates") upward along magnetic fields at high velocities of 200–400 km s^{-1} (Antonucci et al. 1982), at which point coronal X-ray emission rapidly increases and produces an "X-ray flare". It is important to realize that the X-ray event and its hot coronal plasma are the end-products of a chain of energy transformations beginning with convective motions at the loop footpoints that jostle magnetic fields and therefore bring non-potential energy into coronal magnetic loops.

Many of these steps can be inferred also for stellar flares. Photospheric and chromospheric heating in the early phases of flares is clearly seen in ultraviolet or "U band" bursts (Hawley et al. 2003), and the accompanying radio emission has been recorded in non-thermal gyrosynchrotron bursts (Kundu et al. 1987). The characteristic time delay between these "prompt" emissions, tracing the energy input rate, and the gradual X-ray radiation, tracing the accumulated energy in the coronal loop systems, is described by the "Neupert effect" (after Neupert 1968) which states that the X-ray light curve is approximated by the time integral of the radio and optical light curves, or that the time derivative of the increasing X-ray light curve is proportional to the fluxes of the optical and radio bursts. This is so far—based on the solar analogy—the clearest indirect evidence for systematic mass motions in chromospheric evaporation in stars; the Neupert effect has been recorded in flares from M dwarfs (Hawley et al. 1995; Güdel et al. 1996, 2002b) and RS CVn binaries (Güdel et al. 2002a; Osten et al. 2004).

Measuring actual mass motions during flares has remained much more difficult. Accompanying motions of hot gas with temperatures around 10^4 K have been seen in the optical and ultraviolet (Gunn et al. 1994; Hawley et al. 2003; Fuhrmeister and Schmitt 2004), and the ultraviolet "coronal" Fe XIII line also indicated some line-of-sight velocities in a strong flare on CN Leo (Fuhrmeister et al. 2004). Some of this gas may be related to the initial upflow and—for redshifted lines—later downfall of associated prominence gas. To our knowledge, evaporative mass motions have not yet been measured in stellar X-ray spectra; this is perhaps little surprising given the limited velocity resolution (similar to the expected velocities) and the low flare X-ray luminosity in the early flare phase when the mass motions are most prominent and their velocities are highest. In later flare phases at X-ray maximum, most of the plasma is expected to be in slow motion or stationary.

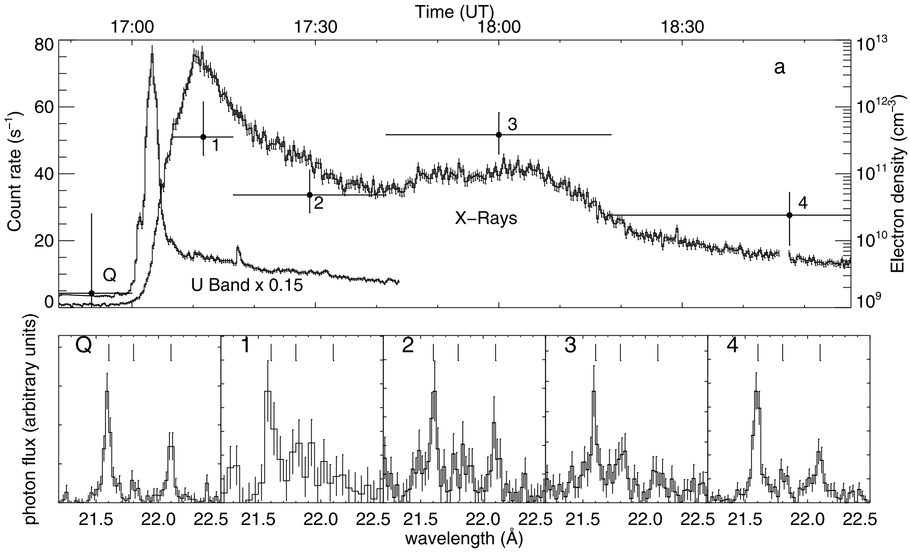

Fig. 2 Evidence for chromospheric evaporation in a flare on Proxima Centauri. The *upper panel* shows the X-ray light curve together with a U band burst at about 17:05 UT. The *large crosses* show electron densities averaged over the intervals defined by the horizontal arms (see right *y* axis). The O VII triplets for the five intervals are shown in the *bottom panel* for the various flare intervals (adapted from Güdel et al. 2002b, with kind permission from Springer Science+Business Media)

Large solar events are often accompanied by coronal mass ejections (CMEs). Again, X-ray spectroscopic kinematic evidence for CMEs is not available, but optical and UV spectroscopy has indicated such events with gas flow velocities up to 5800 km s^{-1} (Houdebine et al. 1990, 1993; Fuhrmeister and Schmitt 2004).

An entirely different way to infer chromospheric evaporation during flares is through the measurement of electron densities in the flaring plasma, e.g., using He-like triplets of O VII or Ne IX. First significant stellar X-ray spectroscopic evidence for a density increase in a flaring coronal source was seen in Proxima Centauri (Güdel et al. 2002b). During two flare maxima, the forbidden line in the O VII triplet nearly disappeared while the intercombination line was prominently present, indicating plasma densities up to 4×10^{11} cm^{-3}, up from $<10^{10}$ cm^{-3} before the flare (Fig. 2). The instantaneous energy in the thermal plasma emitting the O VII line was much smaller than the integrated, emitted energy in the soft X-ray band, necessitating continuous replenishment of cool plasma during the flare, most probably from ongoing cooling of initially much hotter plasma.

Mass motions may also leave traces in the composition of the coronal plasma. From solar physics, a fractionation process has been suggested for the coronal plasma, resulting in relative abundances in the corona that depend on the first ionization potential of the element. Elements with a FIP below ≈10 eV (such as Mg, Si, Fe) are overabundant relative to the photospheric mixture by a factor of a few although the coronal composition varies between different features and in time (Feldman 1992). It came as a surprise when X-ray spectroscopy showed an inverse trend for magnetically active stars, suggesting an overabundance of high-FIP elements such as C, N, O, and Ne compared to low-FIP elements, although all elements tend to be underabundant compared to the photosphere (Brinkman et al. 2001; Audard et al. 2003). The cause for this anomaly remains unclear but unresolved flares have been suggested to drive the "inverse FIP" (IFIP) effect (Brinkman et al. 2001).

There are two further, related trends. The IFIP effect gradually weakens and reverses to a FIP effect as magnetic activity decreases in the course of stellar evolution (Telleschi et al. 2005). On the other hand, the strength of the IFIP or FIP effect also depends on the spectral type of the star in the range of G–M, later-type stars attaining stronger IFIP anomalies than earlier-type stars at comparable activity stages (Telleschi et al. 2007; Güdel et al. 2007; Scelsi et al. 2007). Evidently, surface properties such as $T_{\rm eff}$ control the abundance fractionation.

Abundances may change during flares. There is evidence that in magnetically active stars flares enhance low-FIP elements in the corona in such a way that the IFIP effect may disappear and the coronal low-FIP abundances reach photospheric values (e.g., Osten et al. 2000; Audard et al. 2001). A systematic clarification was provided by Nordon and Behar (2007, 2008) from X-ray spectroscopy of stellar flares. They performed abundance analysis relative to the quiescent state, circumventing the problem of the often unknown photospheric abundances. Stars which, in quiescence, show an IFIP effect tended to systematically produce flares with a relative FIP effect, while stars with a normal FIP effect in quiescence produced flares with a relative IFIP trend. This observation suggests that fresh, unfractionated photospheric/chromospheric mass is transported into the corona in the course of a flare.

3 Flows in Pre-main Sequence Stars

Low-mass stars in phases preceding their main-sequence life are thought to be magnetic in a similar way as their older zero-age main-sequence analogs. They emit X-rays near the empirical saturation limit ($L_{\rm X}/L_{\rm bol} \approx 10^{-3}$), show flares, and also provide all further evidence for magnetic activity across the electromagnetic spectrum. Similar mass flows are undoubtedly present in their coronae as in main-sequence or post-main sequence stars or in the Sun.

Pre-main sequence stars, in particular classical T Tauri stars (CTTS), show a more dynamic environment than more evolved stars, however. Specifically, circumstellar disks, accretion flows, and outflows with jets enrich the picture. Can X-ray spectroscopy contribute to studies of mass flows in this larger circumstellar environment?

3.1 X-Rays from Accretion Flows

Accretion streams are thought to fall toward the star in near-free fall starting from the inner disk at the co-rotation radius. Resulting velocities are close to the escape velocity (several 100 km s^{-1}). The downfalling material forms a shock near the stellar surface in which temperatures of about $T = (3/16k)m_p\mu v_{\rm m}^2$ are expected. Here, k is the Boltzmann constant, μ is the mean molecular weight, m_p is the proton mass, and $v_{\rm m}$ is the pre-shock velocity. For typical fall velocities, T is a few million K. At the same time, depending on the mass accretion rate and the stellar surface filling factor of the accretion streams, high densities up to 10^{12}–10^{13} cm^{-3} are expected. X-ray spectroscopy is ideal to study plasma in these temperature and density regimes.

T Tauri stars were indeed found in the early days of high-resolution X-ray spectroscopy to show anomalous f/i flux ratios in He-like triplets of O VII and Ne IX. The first example was TW Hya, indicating electron densities as high as $\approx 10^{13}$ cm^{-3} at temperatures of only a few MK (Kastner et al. 2002). Such densities are never found in non-flaring stellar coronae, which suggested that accretion shocks are indeed the source of TW Hya's soft X-rays. Similar densities were later found in other CTTS as well although the sample remains very small, given the relatively faint triplets from these stars (e.g., Stelzer and Schmitt 2004). Models of plane-parallel shocks self-consistently explain the observed densities and temperatures of the shocked plasma, and can even be used to estimate mass accretion rates and (usually rather small) filling factors (Günther et al. 2007). Numerical simulations fully confirm this picture (Sacco et al. 2008).

The picture of accretion-induced X-ray emission still faces some problems for which more sophisticated models are needed. One is the absorption of soft X-rays to be expected from the overlying, incompletely ionized accretion streams. Assume a post-shock density of 4×10^{11} cm^{-3} as measured in some examples, implying a pre-shock density of 10^{11} cm^{-3}, and further assume a column height of only 10^{11} cm, i.e., of order one stellar radius. The expected (neutral) column density of 10^{22} cm^{-2} would clearly absorb the O VII triplet. Accretion flow curvature could diminish this problem, but on the other hand, some of the shocked material may be buried in the photosphere as well (Drake 2005).

Further, post-shock material should cool with increasing distance from the shock, i.e., toward deeper layers below the shock surface (Fig. 4a). At the same time, the density should increase in the same direction. One would therefore expect higher absorption and higher densities for O VII than for Ne IX or Mg XI. The contrary is the case. Brickhouse et al. (2010) report clearly lower densities (6×10^{11} cm^{-3}) and absorbing hydrogen column densities (4.1×10^{20} cm^{-2}) for O VII than for Ne IX (3×10^{12} cm^{-3} and 1.8×10^{21} cm^{-2}, respectively). A potential resolution of this contradiction is summarized below.

3.2 The Soft Excess of CTTS

Another spectral anomaly of CTTS refers to the relative flux in the O VII He-like triplet compared to the O VIII Lyα line. Compared to main-sequence stars and also (non-accreting) weak-lined T Tauri stars (WTTS), CTTS show a clear excess of O VII emission by a factor of about 4–5, which is an expression of the "X-ray Soft Excess" (Güdel 2006; Telleschi et al. 2007; Güdel and Telleschi 2007; Fig. 3). The excess in the flux ratio could in principle be due to a suppression of the O VIII flux but such a suppression is not found when comparing the O VIII Lyα line luminosities of CTTS with those of main-sequence stars (e.g., as a function of the total X-ray luminosity). Therefore, the X-ray soft excess indicates a relation with accretion (only CTTS show an excess) *and* coronal activity (the O VII flux excess is roughly correlated with the coronal O VIII Lyα flux). Does the soft excess therefore indicate an interaction between accretion streams and the coronal magnetic field? For example, the presence of accreting, excess material at coronal heights heated to moderate temperatures in the corona by the "coronal heating mechanisms"?

Brickhouse et al. (2010) suggested that the O VII radiation from TW Hya previously attributed to deep shock layers is in fact the "splash" of the stellar photosphere heated by the accretion flow; material is fed back into adjacent coronal loops, thus perhaps explaining the soft excess and its relation to magnetic activity (Fig. 4b).

4 Stellar Winds in Hot Stars

In every high-energy phenomenon related to massive stars, the expanding stellar winds play a major role. These outflows directly control the intensity, hardness, and variations of the X-ray emission, be it from single stars or multiple systems. However, the exact physical properties of these winds, such as mass-loss rates and structure, are still vividly debated in the community at the present time (Sundqvist et al. 2010). In this context, X-rays provide an independent diagnostic tool, hence crucial information to understand a phenomenon which can have consequences on a galactic scale.

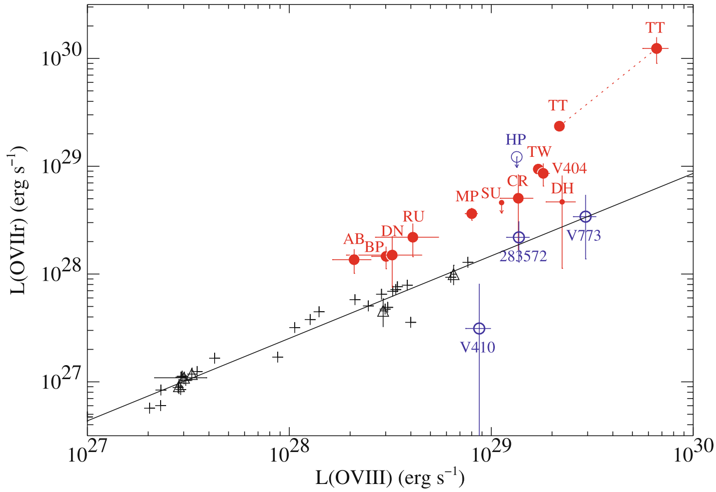

Fig. 3 The X-ray soft excess of classical T Tauri stars. The figure plots the luminosity in the resonance line of the O VII He-like triplet against the coronal O VIII Lyα luminosity. The two luminosities are well correlated in coronal stars on the main sequence (*black symbols* and *black solid* regression fit) and in weak-lined T Tauri stars (*blue symbols*), while there is a clear O VII excess in classical T Tauri stars (*red symbols*; adapted from Güdel and Telleschi 2007, reproduced with permission ©ESO)

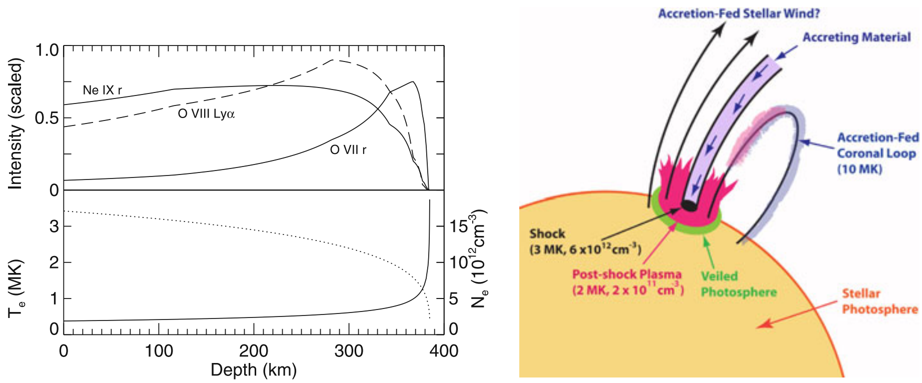

Fig. 4 *Left:* The lower panel shows the run of temperature (*dotted*) and electron density (*solid*) in the post-shock region of an accretion shock (located at depth 0). The *upper panel* plots the fractional contributions to the line intensities for Ne IX, O VIII Lyα, and O VII r. (From Brickhouse et al. 2010.) *Right:* Sketch interpreting various X-ray emitting regions around an accretion shock, including a post-shock zone and accretion-fed coronal loops (from Brickhouse et al. 2010, reproduced by permission of the AAS)

4.1 Winds of Single Stars

Stellar winds are born from the intense UV emission of hot stars. As the line-driving mechanism is intrinsically unstable, shocks arise in the expanding outflow. Strong reverse shocks can heat the plasma to high temperatures, resulting in soft X-ray emission (Owocki et al. 1988). This paradigm is generally called the "wind-shock" model.

The predicted thermal X-ray emission is therefore intimately linked to the wind characteristics. As the X-ray emission arises in an expanding wind, the associated X-ray lines

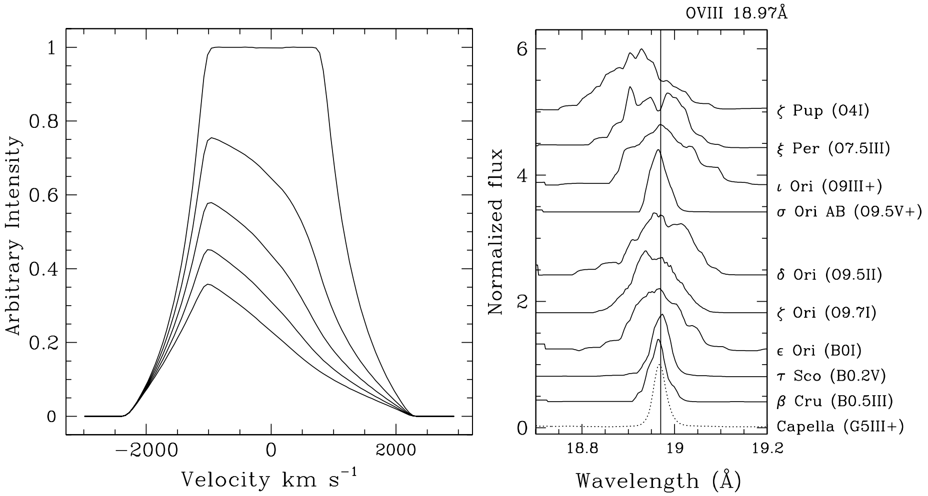

Fig. 5 *Left:* Theoretical X-ray line profiles for a wind with $v_\infty = 2300$ km s^{-1}and increasing opacities, from 0 to 2 in steps of 2.5. (Figure courtesy of G. Rauw.) *Right:* Observed line profiles for O VIII in a sample of bright OB stars and in the coronal giant Capella. The *vertical line* gives the rest velocity. Line profiles have been shifted arbitrarily along the y axis for illustration purposes (from Güdel and Nazé 2009, with kind permission from Springer Science+Business Media)

should be broad, the width being a large fraction of the wind terminal velocity (i.e. 1000–4000 km s^{-1} in such stars). In addition, as the strongest emitting shocks should occur only at a few stellar radii from the photosphere (Feldmeier et al. 1997), the f/i ratio of the He-like triplets is expected to be low. Indeed, at such distances, the UV emission of the star is not much diluted and is therefore able to depopulate the upper level of the f transition, hence weakening this line. In the same process the upper level of the i transition is populated, hence strengthening that line. Finally, as the produced X-rays have to cross the stellar wind before reaching the observer, the X-ray lines are expected to suffer from absorption effects. While in the optically-thin case the line profiles should appear flat-topped, the X-ray lines arising in more absorbed winds should appear blueward-skewed, as the redshifted part of the emission, associated with the backside of the star's atmosphere (as seen from the observer's point-of-view), has to cross more wind material and thus suffers from more absorption than the blueshifted part (Fig. 5). The departure from symmetry increases with the opacity of the wind. Models calculating such line profiles were presented by Macfarlane et al. (1991) and Owocki and Cohen (2001).

With the advent of Chandra and XMM-Newton, the first high-resolution spectra of hot stars became available. The detailed line profile revealed mixed results. While the observations of ζ Pup (O4Ief) agreed rather well with the above predictions (Kahn et al. 2001; Cassinelli et al. 2001), other stars yield rather different results (for a review, see Güdel and Nazé 2009). For example, for the late-type stars ζ Ori A (O9.7Ib), δ Ori A (O9.5II+B0.5III), ζ Oph (O9.5Ve) and σ Ori AB (O9.5V+B0.5V), the lines are not only narrower than in the case of ζ Pup (especially for σ Ori AB), but also symmetric and unshifted—or at most slightly blueshifted (Waldron and Cassinelli 2001; Miller et al. 2002; Waldron 2005; Skinner et al. 2008). The general picture that emerges from these observations is that the X-ray lines arising from stellar winds are not as broad, asymmetric, blueshifted and wavelength-dependent as expected. The opacity also appears reduced compared to predictions made on the (then suspected) mass-loss rates.

To explain the high-energy data, changing the "canonical" model was necessary. Refinements of the physics, such as the inclusion of resonance scattering (Ignace and Gayley 2002), were proposed, but are not sufficient to explain the observations. The best solution, in the context of the wind-shock paradigm, is reducing the mass-loss rates (e.g. Cohen et al. 2006). Indeed, the recent inclusion of clumping in the analysis of UV/optical spectra naturally led to a reduction of such rates (see e.g. Bouret et al. 2005), corroborating the conclusions derived from X-ray data. Clumping could also have another consequence: porosity. In the case of dense clumps, the radiation can avoid absorption by passing in between these structures, leading to a geometric opacity, even independent of wavelength in the optically-thick case, rather than an atomic one which is highly wavelength-dependent (Feldmeier et al. 2003; Oskinova et al. 2006). The resulting X-ray lines are more symmetric and less blueshifted than in the original wind-shock model.

Two additional solutions were advanced. Waldron and Cassinelli (2009) proposed to consider a corona at the base of the wind, where velocity is low, to explain the (potentially different) properties of lines arising from highly ionized elements. Pollock (2007) suggested to include the effect of magnetic fields, considering the shocks to be collisionless and the plasma to be out-of-equilibrium, to explain the discrepant shape of the X-ray lines. In the latter case, a detailed modeling is still missing for a full comparison of predictions with observations.

Up to now, only line profiles averaged over a (generally single) whole exposure have been analyzed. It is however well known from the visible domain that emission lines, i.e. lines arising in the stellar winds, can vary, revealing the presence of wind structures (e.g. corotating structures, Cranmer and Owocki 1996). Such features should be even more ubiquitous in the high-energy range as they produce shocks in the winds. Therefore, the future of X-ray analyses of single massive stars does not only require studying larger samples in order to clarify the global wind parameters, but also performing temporal monitoring of the line profiles in the X-ray domain, to study the wind structure in detail.

4.2 Colliding Winds in Massive Binaries

Many hot stars are found in multiple systems. When observed in X-rays, the emission of such systems is not always[1] the simple addition of the individual wind-shock emissions. Indeed, when two strong stellar winds are present in a binary, they can collide face-on in-between the stars. These strong shocks produce very hot plasma, hence hard X-ray emission. In such cases, the total X-ray emission of the system will then be brighter and harder than expected from the two individual stars as it will consist of both a soft component from the intrinsic emissions and a hard component related to the colliding winds (CW).

A typical signature of CW emission is its modulation with the orbital phase. The origin of these variations can be twofold. First, the absorption along the line-of-sight changes with phase, as the CW zone is alternatively seen through two (generally) different stellar winds. This absorption effect can be quite dramatic for very asymmetric winds, e.g. WR+O binaries (see the case of γ^2 Vel, Willis et al. 1995). Second, changes can appear in the strength of the CW emission itself in eccentric binaries. For short-period systems, theory predicts the collision to be radiative and the CW zone to be rather turbulent. The X-ray luminosity should scale as $L_X \propto \dot{M} v^2$ (Stevens et al. 1992), thus decreasing as the stars get closer since

[1] Contrary to a vivid urban legend, X-ray bright collisions are actually quite rare among massive binaries, as was demonstrated in the last decade by observing clusters with well-known stellar populations (e.g., Sana et al. 2006; Nazé 2009).

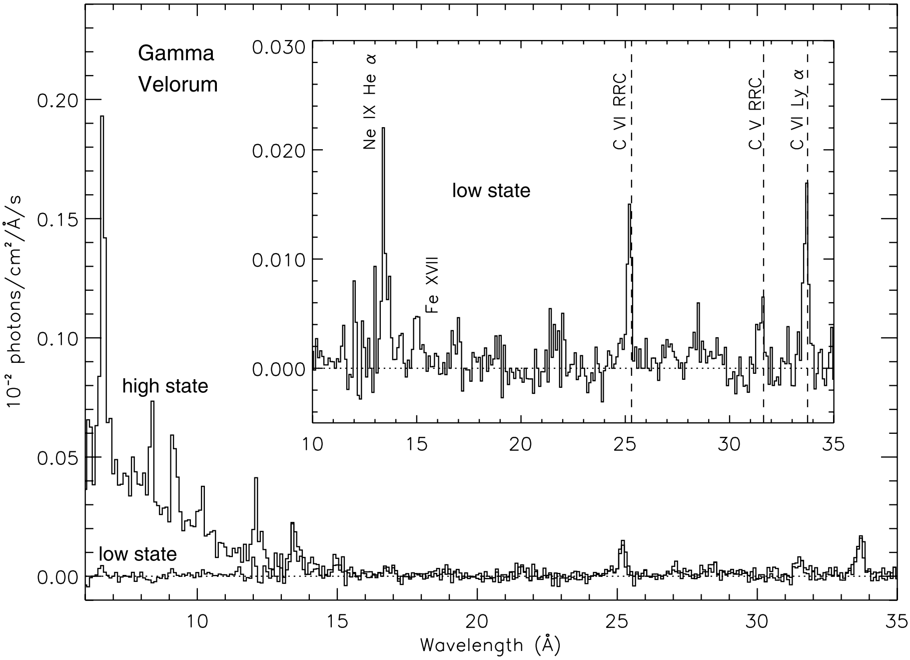

Fig. 6 X-ray spectrum of the WR+O star binary γ^2 Vel obtained at the X-ray maximum ("high state") and at X-ray minimum ("low state"). The inset shows the long-wavelength portion of the spectrum with radiative recombination continua (RRC; from Schild et al. 2004, reproduced with permission ©ESO)

the collision then occurs inside the wind acceleration zone. For long-period systems, the collision is adiabatic, and the X-ray luminosity should rather follow $L_X \propto \dot{M}^2 v^{-3/2} D^{-1}$. In this case, the X-ray luminosity increases as the stars get closer and the wind density is larger. Clear variations of the X-ray luminosity between apastron and periastron have been detected in several cases (for a review, see Güdel and Nazé 2009).

Only a few CW systems have been observed at high spectral resolution but they provided invaluable clues on the CW physics. Some basic expectations can be underlined: (1) as the CW zone, shaped as a cone folded around the star with the weaker wind, is located quite far from the stars themselves, the f/i ratios of the X-ray lines should be less affected by the UV radiation field, (2) the lines should be broad as the X-rays are linked to high-velocity winds, but the actual width could vary with the viewing angle on the CW zone, (3) the line shift should depend on the viewing angle of the observer on the CW zone.

The binary γ^2 Vel (WC8+O7.5III) was observed by both Chandra and XMM-Newton gratings (Skinner et al. 2001; Schild et al. 2004; Henley et al. 2005; Fig. 6). The X-ray lines appeared clearly broad (FWHM of 1000–1500 km s^{-1}), without asymmetries or large shifts (-64 ± 12 km s^{-1} on average). The forbidden line is indeed stronger than in single stars but Henley et al. (2005) found differences among ions, with the Mg XI line arising from hotter gas located closer to the O star than, e.g., the Si XIII line. This could happen if the hot plasma is out-of-equilibrium. In addition, the negligible line shifts disagree with results from theoretical modeling of the CW zone as long as the shock opening angle is small (a fact expected from the shape of the X-ray light curve). However, if some sudden radiative braking occurs near the binary axis, the opening angle could widen in that region and explain the line observations (Henley et al. 2005).

Two Chandra observations of WR140 (WC7+O4–5) were reported by Pollock et al. (2005). The pre-periastron data revealed symmetric but blueshifted lines (-600 km s^{-1}). These blueshifts can be easily understood in terms of the system's geometry, as the line-of-sight was then aligned with one side of the shock cone. In addition, the line widths vary from line to line (from <1000 km s^{-1} to more than 2000 km s^{-1}, with an apparent increase with ionization potential). Pollock et al. (2005) therefore suggests the plasma to be out-of-equilibrium, implying an evolution of the ionization of the gas in the wind-wind collision zone: low-ionization elements such as O VIII and Ne IX, which display relatively narrow lines, would be more confined near the stagnation point than, e.g., plasma associated with Si XIV emission. The situation would be similar for He-like triplets vs H-like lines of the same elements. Moreover, the f/i ratios are large, possibly exceeding the upper limits derived for low UV fluxes and low densities. If confirmed, this would be additional evidence in favor of non-equilibrium (the forbidden line being boosted by inner-shell ionization of Li-like ions which would temporarily appear before the establishment of the equilibrium). In the post-periastron observation, WR140 was much fainter and only a few lines could be analyzed but they showed very different velocity structures: broader lines with marginal redshift, and even a double-peaked profile seen in Si XIII. This is again broadly consistent with the system's geometry at that phase. Clearly, a more intense monitoring of the system, obtained at higher sensitivity, would probe all facets of the collision zone, boosting our understanding of the phenomenon.

The spectrum of θ Mus (WC5/WC6+O6/O7V, plus probably O9.5/B0Iab) was also the target of an XMM-Newton observation (Sugawara et al. 2008). The strongest line, that of O VIII, showed a clear redshift ($\sim$600 km s^{-1}) and a non-negligible width (FWHM $\approx$ 1400 km s^{-1}); the results for other X-ray lines are similar, but with large errors. As in the other two cases, the f/i ratios are again large, suggesting an emission region located far from the UV sources. From these characteristics, Sugawara et al. (2008) inferred that the X-rays arise on one side of the colliding-wind region. However, if the ephemeris is correct, then the geometry of the short-period binary is not compatible with the observations of such a redshift at that orbital phase; Sugawara et al. (2008) rather suggested the high-energy emission to arise in the wind-wind collision zone between the short-period binary and the widely separated supergiant, which would then be the third component of the system and should lie behind the close binary (as seen from the observer's point-of-view).

Apart from the usual X-ray lines, the high-resolution spectra of γ^2 Vel (Schild et al. 2004) and θ Mus (Sugawara et al. 2008), both WC+O systems, also indicate the presence of narrow radiative recombination continua (RRC) associated with highly ionized carbon (C V, C VI; see Fig. 6). The shape of the RRCs at high energies depends on the temperature of the recombining electrons: in both cases, a low temperature of a few eV was derived. At such temperatures, radiation, rather than collisions, is the dominant ionization process and the X-rays from the CW zone itself could be the source of that radiation. In the absence of phase-locked variations, Schild et al. (2004) suggested the recombination to occur far out in the system. For θ Mus, as data may suggest the RRCs to display a similar shift as the X-ray lines, Sugawara et al. (2008) proposed the RRCs to be linked with the hot gas in the CW region (through diffusion or convection of highly ionized elements followed by electron exchange with the cooler stellar wind).

Future facilities will enable us to study the X-ray lines in more detail, which will be crucial to constrain the wind parameters. In this context, it is important to note that further theoretical predictions as well as additional observational techniques are already available.

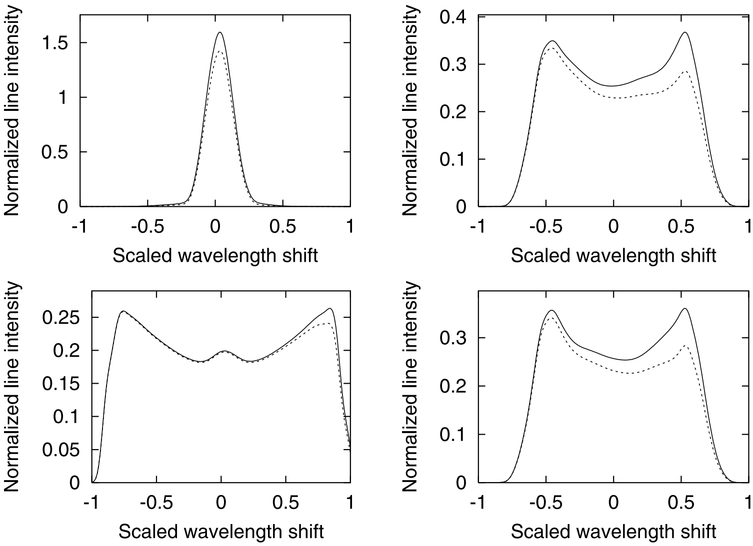

Fig. 7 Modeled Mg XII Lyα line profiles for a colliding-wind shock (*solid*: unabsorbed; *dashed*: absorbed), for various viewing angles: $\theta = 0$ (*top left*), $\theta = 45$ deg (*top right*), $\theta = 90$ deg (*bottom left*), and $\theta = 135$ deg (*bottom right*; from Henley et al. 2003, reproduced with permission by John Wiley & Sons Limited)

Theoretical line profiles have been calculated by Henley et al. (2003) for various orbital configurations and stellar parameters (Fig. 7). The resulting lines show a wide range of shapes. If two winds of similar momenta ($\dot{M} \times v_\infty$) collide, the intrinsic X-ray lines should appear symmetric and unshifted (typically with ~Gaussian profiles); if two winds of different strengths collide, the lines shift from the blue (when seen from the secondary's side) to the red (when seen from the primary's side) with a dependence linked to the shock opening angle, i.e. the wind momenta ratio. In addition, the line width would also vary with the viewing angle: when seen along the binary axis, the velocity spread is much smaller than at quadrature (where the FWHM $\approx 2 \times v_\infty$). Moreover, the line profiles change from symmetric (~Gaussian) in the former case to flat-topped (with two peaks at the edges). Taking into account the wind absorption results in blueward-skewed lines, for the same reasons as for the embedded wind-shock model. Indeed, the orbital variations in line width, shift and profile are less prominent in a binary seen at a low orbital inclination. Note also that, even if the CW zone is turbulent, the associated variability is only a few percent of the line profile, i.e. much smaller than the viewing effects.

Observational techniques also exist that can directly map the zone where emission lines arise. The most important one is Doppler tomography, which has been widely used in the visible domain for cataclysmic variables, Algol binaries, and also colliding-wind binaries (for some examples, see Thaller et al. 2001; Rauw et al. 2005). This technique relies on the detailed analysis of a circular binary system in the velocity space. Axes are anchored to the center-of-mass of the binary, with the x-axis defined as the binary axis and the y- and z-axes as the two perpendicular axes to the x-axis (y-axis being in the orbit plane, z-axis perpendicular to it). An emission component arising at a given position in the binary system will then have fixed v_x, v_y, v_z coordinates. Relative to that coordinate system, the observer seems to rotate, thereby seeing the emission components under different viewing angles. While the intrinsic emission is not varying, the observed one does change because of projection effects, as the resulting line profile is the integration of the emission zone components along the line-of-sight. In practice, the method uses retro-projection, searching the intensity distribution matching best the observed variations of the line profile. Its application to X-rays should be rather straightforward, as it can be easily applied to, e.g., the strong Fe K line, and would then yield unique information on the hydrodynamics of stellar winds (Rauw 2010).

4.3 Wind Confinement by Magnetic Fields

Magnetic fields, when strong enough, can have a strong impact on the wind structure, hence on the X-ray emission. ud-Doula and Owocki (2002) showed that the impact can be easily assessed from the confinement parameter $\eta = B_{\rm eq}^2 R_*^2/(\dot{M} v_\infty)$: if $\eta \ll 1$, the outflowing wind remains rather unaltered by the weak magnetic field; if $\eta > 1$, the magnetic field controls the outflow of ionized material close to the star. In the latter case, the winds from both stellar hemispheres are channeled towards the magnetic equator, where they collide face-on. This phenomenon produces hard emission close to the star, with little radial velocity: the X-ray lines are thus expected to be narrow, only slightly (blue)shifted, and associated with elements of high ionization levels; in addition, the f/i ratios should yield plasma formation regions very close to the star. These theoretical predictions fit quite well the observations of θ^1 Ori C and τ Sco (Gagné et al. 2005; Mewe et al. 2003). Lines arising from lower temperatures (hence most probably not linked to magnetic confinement) appear even broader, as should be expected if they are associated with embedded wind shocks. However, the magnetically-channeled wind model does not explain the case of other magnetic objects, like the Of?p stars whose X-ray emission appear less hard with lines broader than expected on the basis of their confinement parameter (Nazé et al. 2010). Most probably, a better knowledge of the exact magnetic configuration as well as of the stellar parameters will be able to solve this discrepancy.

It must further be noted that magnetic fields are also seen as a potential solution to the surprising X-ray emission from B stars. Their high-resolution spectra cannot be explained by the wind-shock model but their weaker stellar winds are more easily confined than those of O stars, and the observation of narrow X-ray lines as well as close formation radii appear reminiscent of magnetic confinement. Detailed modeling is still missing, though (see Güdel and Nazé 2009 and references therein).

Finally, in addition to improved modeling, better observations are needed. MHD simulations have shown that the magnetic confinement does not produce a stable "disk" around the star. Rather, mass builds up in the equatorial region, then either falls back on the star or is ejected outwards (ud-Doula et al. 2006). Such episodes can give rise to X-ray flares and changes in the line profiles. A study of this short-term variability requires a high sensitivity and would provide invaluable information on the magnetic confinement phenomenon.

5 Conclusions

X-ray studies of kinematics and mass motions in stellar atmospheres and stellar environments require high-resolution spectroscopy with a resolving power of at least a few hundred. XMM-Newton and Chandra have opened this new area of X-ray research and have provided interesting new evidence both for hot stars and cool stars. Kinematic information from line broadening and line shifts for late-type binaries has given important clues on the location and extent of stellar coronal X-ray sources complementary to information obtained from other methods (e.g., using eclipses or light curve modulation).

Investigations of mass motions in stellar coronae are more subtle. In principle, X-ray spectroscopy could probe evaporating flows during energy release events, but so far we are relying on more indirect ways of inferring the presence of such flows, such as He-like triplet analysis indicating density increases in closed magnetic fields. The solar analogy has been pivotal to understand such observations.

In accreting pre-main sequence systems, accretion flows produce shocks near the stellar surface. Models predict X-ray emission from these shocks, but again, the main X-ray spectral information on these flows comes from the analysis of density-sensitive lines rather than from kinematic information.

The area of hot stars has seen considerable boost from the analysis of line profiles in X-rays, ascribed to X-rays from shocks in an expanding wind. Both shock velocity and absorption by the wind shape the line profiles. Very luminous shocks are produced in colliding wind binaries; again, kinematic line profile information has provided important clues on the flow direction and speed in such shocks, and thus eventually on the geometry of the colliding shock zone.

Clearly, this field of X-ray astronomy is only at the beginning. While first important contributions have been made from the analysis of line shifts and profiles, higher resolution is needed. Most flows expected in the atmospheres of cool stars and pre-main sequence stars reach velocities of no more than a few 100 $\mathrm{km\,s^{-1}}$, and signatures of such flows may be superimposed on emission from stationary plasma. Subtle details of line profiles from hot stars require high resolution as well, together with appropriate sensitivity. We expect this field of research to obtain a new, strong boost with the advent of the International X-ray Observatory (IXO) that will provide both the required spectral resolution and sensitivity to address many of the open points.

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