Stars

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Innovative measurements of stellar mass loss

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Analysis of archival XMM-Newton data yields measurements of stellar wind emission from three star systems, illustrating a direct method to determine the mass-loss rates of late-type main-sequence stars.

Stellar winds from massive hot stars (O and B type) and giants near the end of their lives can be several orders of magnitude stronger than those from smaller 'late-type' stars like the Sun, and have been measured for many stars using techniques based on radio, infrared, and ultraviolet emission. In contrast, the comparatively feeble winds from main-sequence M, K, G, and some F stars, which originate in the million-degree coronae surrounding such stars, are much more difficult to detect. The most successful method, measuring absorption in the wings of a star's hydrogen Lyman-α line[1], has been applied to over a dozen nearby stars, but is indirect and requires detailed modelling of the emission line in order to reveal the subtle signature of absorption by neutral H that is swept up by the stellar wind. As explained in a paper in *Nature Astronomy*, Kristina Kislyakova and colleagues[2] have used a more direct method to detect the winds of three nearby star systems, and they estimate the stars' mass-loss rates by observing X-ray emission from their stellar winds, which can be spectrally and spatially distinguished from the much stronger point-source-like coronal emission.

The wind emission comes from a relatively obscure atomic process called stellar wind charge exchange (SWCX). For our Sun, this process predominantly occurs via collisions between the solar wind's fast-moving hydrogen ions and neutral H from the interstellar medium (ISM) flowing through the heliosphere. During charge-exchange collisions, an electron from a neutral atom is transferred to the ion, and the now-neutral but still fast-moving hydrogen from the wind piles up around the edges of the heliosphere (or 'astrosphere' when around another star) in a 'hydrogen wall'. This wall produces the absorption signature used in the Lyman-α technique mentioned above. That H-atom/H-ion charge exchange usually occurs without producing any photons, but SWCX can also produce X-ray emission when highly charged 'metal' ions within the wind – particularly fully ionized (bare) and hydrogenic (one-electron) oxygen – collide with neutral H and He and capture an electron into an excited energy level that then radiatively decays[3].

SWCX X-ray emission was first recognized in comets[4], where the solar wind collides with neutral gases such as H_2O and CO_2 sublimating from the comet. Next came the explanation for the 'long term enhancements' seen in the ROSAT All-Sky Survey[5], in which varying levels of background X-ray emission were seen in multiple scans of a given slice of sky. These translated to variations in the density and speed of solar wind impacting the Earth's tenuous outer atmosphere of neutral H (ref. 6). That exospheric, or geocoronal, SWCX emission can vary on timescales of minutes, but for satellites in low Earth orbit like ROSAT, its observed intensity is usually about an order of magnitude weaker than heliospheric emission, which originates over many astronomical units and therefore responds over longer timescales to changes in solar wind flux. Many studies of SWCX emission have since been published, comprising X-ray detections of dozens of the Solar System's comets and planets, and roughly half of the X-ray background in ROSAT's 1/4 keV band is estimated to come from SWCX. More recent X-ray observatories generally use CCD detectors rather than ROSAT's proportional counters and cannot observe below around 300 eV, so most X-ray SWCX studies have focused on emission from oxygen around 560 eV.

SWCX must of course also occur around stars other than the Sun, at least when the stars are located within volumes containing a significant fraction of neutral gas, for example, within interstellar clouds. As observed from Earth, a star's coronal X-ray emission (from ion–electron collisions) appears point-like, while the SWCX emission will be spread in a halo (often lopsided, depending on our viewing angle of the astrosphere) extending for tens or hundreds of au from the star. At distances of several light years, this corresponds to a couple of arcminutes; much wider than the typical X-ray telescope resolution of a dozen arcseconds. A few attempts to observe SWCX around other stars were made using the Chandra X-ray observatory, but only an upper limit was obtained for Proxima Centauri, the nearest star[7]. Chandra's unusually good angular resolution of better than 0.5 arcseconds was actually a complication in that analysis because the bright coronal emission caused detector saturation in the image core.

The analysis by Kislyakova et al. uses data from XMM-Newton, which has a spatial resolution good enough to easily sample SWCX halo emission over many resolution elements, but not so good that the much brighter coronal emission at the centre is saturated. The spectrum from the core of the star's image, dominated by coronal emission, can therefore be used as a template when fitting the spectrum from an annulus around the star (Fig. 1), which is a combination of coronal emission from the wings of the telescope's point spread function (PSF) and emission from the faint SWCX halo. Statistically significant excess oxygen emission was detected from three of the seven stellar systems studied, with upper limits for four more, and the stellar mass-loss rates derived from those measurements are consistent with estimates previously obtained using the Lyman-α method. As mentioned above, mass-loss measurements for main-sequence stars are rare, but vital for understanding many aspects of stellar evolution and magnetic-field generation, such as rotational spin-down and the erosion of planetary atmospheres.

The authors plan to analyse data from additional observations, concentrating on stars with higher X-ray fluxes per unit stellar surface area. From previous work using the Lyman-α method, mass-loss rates and X-ray surface brightness are approximately proportional, but this relationship appears to break down for higher brightness stars, particularly for M dwarfs[1]. Higher surface gravity or coronal temperature, stronger magnetic fields, or a more closed field configuration are possible explanations for this phenomenon, but more observational data are needed to understand it fully. New and planned X-ray observatories should be able to study SWCX around dozens or hundreds of additional stars through a combination of larger collecting area, higher counting rate capability, and much better spectral resolution provided

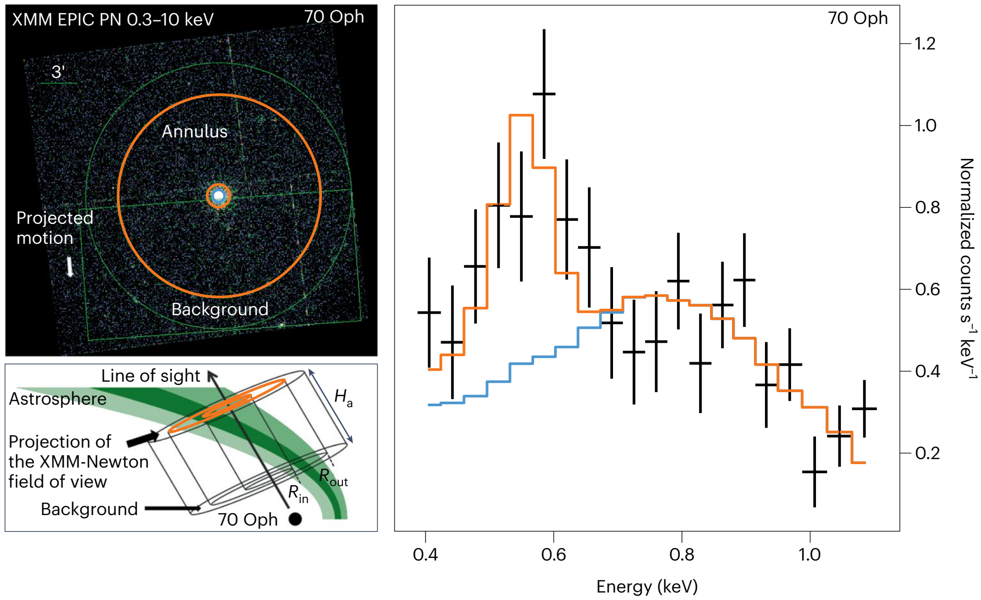

Fig. 1 | Main-sequence star 70 Oph seen in the X-ray. The top left panel is an X-ray image of 70 Oph showing coronal emission in the central blue circle (actually a point source but enlarged by the telescope PSF) and the surrounding annular region (outlined in orange) containing most of the much fainter diffuse stellar wind emission. The bottom left panel shows the observation geometry, with green representing regions of enhanced wind emission along the astrosphere boundary where neutral H piles up. The right panel shows spectra from the coronal (blue) and wind (orange) regions, with the coronal spectrum scaled down to model its contribution (from the wings of the telescope PSF) within the annular extraction used for the wind. The excess (orange minus blue) is from the wind. Adapted from ref. 2, Springer Nature Ltd.

by microcalorimeter detectors instead of CCDs (a few eV instead of roughly 100 eV)[8]. Improved energy resolution could be especially helpful because charge exchange significantly enhances emission from some lines (high-n Lyman lines in hydrogenic ions and the 'forbidden' $n = 2 \rightarrow 1$ lines in He-like ions) relative to electron collisional excitation[3], enabling better SWCX-versus-coronal contrast and perhaps real imaging of astrospheres.

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References

1. Wood, B. E., Müller, H.-R., Zank, G. P. & Linsky, J. L. *Astrophys. J.* **574**, 412–425 (2002).
2. Kislyakova, K. G. et al. *Nat. Astron.* https://doi.org/10.1038/s41550-024-02222-x (2024).
3. Wargelin, B. J., Beiersdorfer, P. & Brown, G. V. *Canadian J. Phys.* **86**, 151–169 (2008).
4. Cravens, T. E. *Geophys. Res. Lett.* **24**, 105–108 (1997).
5. Snowden, S. L. et al. *Astrophys. J.* **454**, 643–653 (1995).
6. Cravens, T. E., Robertson, I. P. & Snowden, S. L. *J. Geophys. Res.* **106**, 24883–24892 (2001).
7. Wargelin, B. J. & Drake, J. J. *Astrophys. J.* **578**, 503–514 (2002).
8. Ishisaki, Y. et al. *Proc. SPIE* **12181**, 121811S (2022).

Competing interests

The author declares no competing interests.