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Resolving Atmospheric Structure in V471 Tauri

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Abstract. The K2V-DA binary V471 Tau has an extended atmosphere. By using the DA white dwarf as a probe, we can probe the atmosphere along the line of sight to the white dwarf with a spatial resolution of order 10,000 km. We observe absorption lines from C II through N V in absorption against the DA photospheric continuum. The velocities are those of gas in co-rotation with the K star.

1. Introduction

The shape and extent of the stellar chromosphere and corona is subject to direct observation only in the case of our Sun, a relatively inactive star. There the strong kilogauss magnetic field is low-lying and tangled, and active region emission arises close to the stellar surface. Evidence from a variety of techniques (e.g., Doppler and Zeeman Doppler imaging, eclipse mapping, VLBI imaging), suggests that the situation in rapidly-rotating active solar-like stars is very different. This evidence is summarized by Walter (1999).

While much of the evidence is circumstantial, or has very low spatial resolution, it is compelling. To quantify the true three-dimensional spatial structure of an active star, we need either better techniques, or we need to get lucky.

We got lucky in the case of V471 Tauri. The K2V star in this eclipsing binary is an excellent analog for the ultra-rapid rotators (URRs). Despite its advanced age (it is a member of the Hyades), it rotates in 12.5 hours. Despite the presence of a white dwarf in the system, the magnetic activity appears similar to that of other URRs. But in this case the the DA white dwarf is viewed through the atmosphere of the K2V star before and after eclipse, providing a pencil beam along which to probe the atmospheric structure of the K2V star on spatial scales comparable to the size of the white dwarf.

By Kirchoff's laws, as the line of sight to the white dwarf sweeps through the K2V atmosphere, the atmosphere will be seen in absorption. In rigid co-rotation, all the gas along the line of sight will have the same radial velocity. One can gain information on the variation of density and temperature with height by observing along a series of lines of sight. The minimum height sampled increases with phase as h_{min} = (a-1) $|\sin(\phi)|$ R_K, where a is the 3.4 R_K semi-major axis of the orbit in K star radii R_K. The time variation of the absorption line profiles therefore probes the density and temperature structure of the atmosphere. This technique has been applied successfully to ζ Aur-type systems (see, e.g., Eaton 1993).

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2. V471 Tauri

The K2V+DA V471 Tau system has an orbital inclination $i \sim 77°$, and a mass ratio ~0.9, with the white dwarf the less massive star. The stars orbital separation is 3.4 R_K (see O'Brien, Bond, & Sion (2001). The K2V star is tidally-locked and rapidly rotating ($V sini$ = 91 km s^{-1}). It is magnetically active, with chromospheric emission and a photometric wave (e.g., Skillman & Patterson 1988), and coronal X-ray emission (e.g., Wheatley 1998). Doppler images (Ramseyer, Hatzes, & Jablonski 1995) reveal a large high-latitude spot. The properties are similar to those of single URRs such as AB Dor and PZ Tel.

Guinan et al. (1986) reported absorption lines of O I, C II, C III, C IV, Si II, and Si IV in the DA continuum between orbital phases ϕ 0.88 and 0.12, as the line of sight passed through the K2V chromosphere. Lines of Si IV and C IV are not expected in a 34,000K DA, and are not seen when the white dwarf is foreground to the K2V star. Guinan interpreted these lines as arising in a chromospheric loop. Sion et al. (1998) and Shipman et al. (1995), respectively, discuss the Si III λ1206Å line and the Si IV $\lambda\lambda$1393, 1402Å doublet, as seen in absorption in *Hubble Space Telescope* (HST) Goddard High Resolution Spectrograph (GHRS) spectra. They interpret this as material accreted onto the DA photosphere.

Jensen et al. (1986) observed dips in the X-ray flux when the white dwarf was viewed through the L_4 and L_5 Lagrangian points (ϕ=0.73, 0.17). They surmised that the dips were caused by enhanced absorption ($n_H \approx 1.5\times10^{19}$ cm^{-2}) by cold ejected material collected in these gravitational potential minima, but they also noted that it could be gas in large magnetic loops. Wheatly (1988) noted one absorption dip in the *ROSAT* data, at ϕ=0.07. He interpreted this as a coronal mass ejection viewed in absorption. Bond et al. (2001) have a similar interpretation for a Si III λ1206Å line seen in absorption.

The white dwarf moves its own radius in about 45 seconds, thus providing independent lines of sight through the K2V atmosphere on this timescale, with a spatial scale of about 15,000 km. The radial velocities of the lines indicate the location of the gas. Gas trapped in magnetic flux tubes along the line of sight will rotate rigidly with the synchronously-rotating K2V star. Deviations from this velocity may be indicative of flows within the loops. The radial velocity of the white dwarf is also the co-rotation velocity, but photospheric features will be shifted by the 50 km/s gravitational redshift. Any gas in Keplerian orbits, or on ballistic trajectories, will exhibit a different velocity signature.

3. Data and Discussion

We obtained 3 GHRS spectra (0.5 sec resolution) with the R=2000 G140L grating, spanning ≈1290Å to 1570Å. All observations sampled ingress phases. The first observation covered those phases where Jensen et al. (1986) observed strong soft X-ray absorption, and revealed strong time variable absorption in O I, C II, Si IV, and C IV. The other two observations, sampling phases closer to ingress (0.93 – 0.97), also revealed variable absorption lines. Significant variability is seen on timescales of a few minutes, providing spatial scales for the absorbing structures of order 10^4 km. The GHRS does not resolve the lines. There is no evidence for the 555 sec white dwarf rotation period in the line variations.

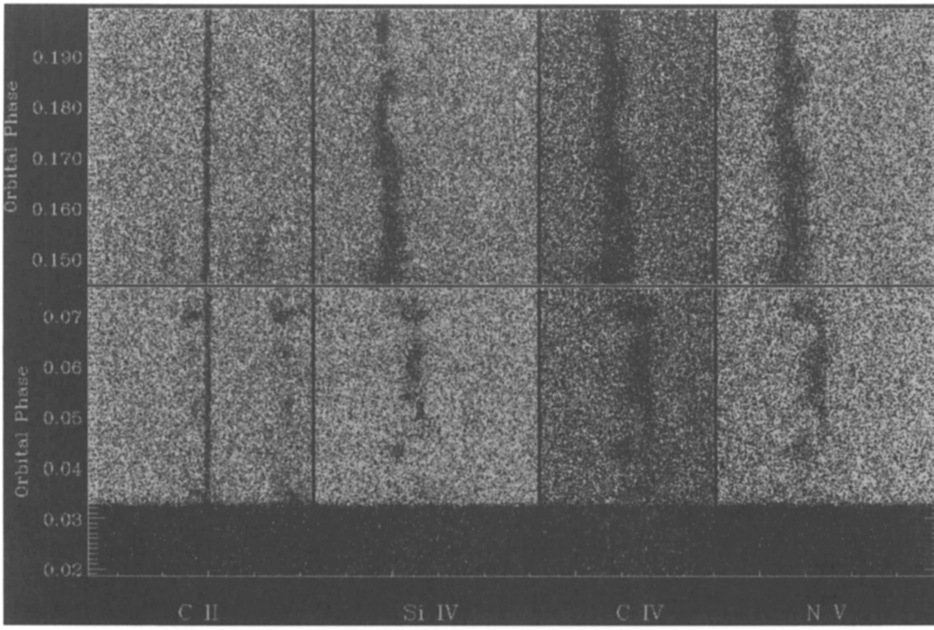

Figure 1. Sections of the time-resolved STIS spectra of 1998 March 13, showing the C II doublet (with a prominent ISM absorption line), Si IV λ1393Å, C IV λ1548Å, and N V λ1238Å. The gap between ϕ=0.07 and 0.15 is due to an Earth occultation. The C II lines are much thinner than the hotter lines, and are not visible at ϕ >0.07. The hotter lines become saturated, with N V remaining saturated at ϕ=0.2 (2.2 R_K above the K2V photosphere), while Si IV is becoming optically thin. The gas temperature increases with height. The absorption follows the radial velocity curve of co-rotating gas (see Fig. 3).

We also observed this system with the HST/STIS. The Space Telescope Imaging Spectrograph (STIS) affords high temporal and spectral resolution (R=40,000) over the $\lambda\lambda$1150-1700Å range. In March 1998 we observed V471 Tau for 6 HST orbits, sampling 4 ingress phases (0.67< ϕ <0.96) and two egress phases (0.02< ϕ <0.20). Once again time variable absorption lines of C II, C III, C IV, Si III, Si IV, and N V were seen (Fig. 1). These data are velocity-resolved: the mean absorption velocity tracks the co-rotation velocity, and not that of any other system component.

The cooler gas, tracked by C II, is only seen close to the photosphere, while the N V saturates at phases approaching quadrature. Si IV, at an intermediate temperature, exhibits a maximum optical thickness near phase 0.15 (Fig. 1). The mean gas temperature increases with height. When the gas is thin, we see discrete structures with spatial scales of a few $\times 10^4$ km. These may be individual flux tubes. While the mean velocities of the gas track the co-rotation velocity (and not the DA photosphere), there are significant deviations, often to the blue, when the lines are thin. These deviations are most pronounced just

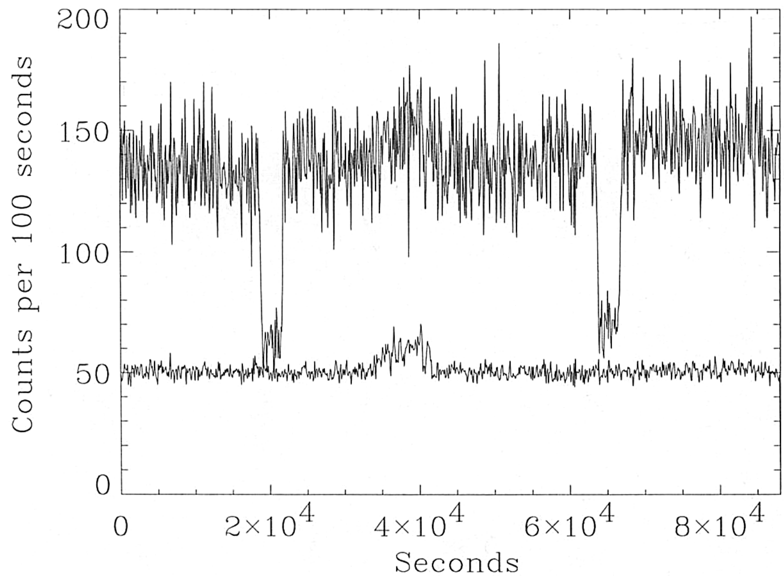

Figure 2. The CHANDRA LETG light curve covering two binary orbits. Two primary eclipses are evident. The eclipses nearly reach the background level (the lower trace): in this band the white dwarf generates ~83% of the X-ray flux. No absorption dips are obvious.

after egress in 1998, when one is presumably looking along, rather than across, the magnetic loops, and may be flows along more-or-less radial magnetic fields.

We obtained an 88 ksec CHANDRA low energy transmission grating (LETG) observation in January 2002 (Fig. 2), along with a HST/STIS observation for 4 HST orbits (Fig. 3), centered on one of the two eclipses. The CHANDRA light curve clearly shows two eclipses of the DA, the dominant soft X-ray source in the system. No prominent absorption dips are evident in the X-ray data.

Comparison of the 1998 and 2002 STIS observations shows that the atmosphere is inhomogeneous on large scales, and this inhomogeneity changes with time. We are working on correlating the location of the absorbing gas with the phase of the starspots. If the gas is trapped in large-scale loops anchored at low latitudes, we expect to see a strong correlation, because the low latitude spots generate the photometric wave.

4. Conclusions

These data verify that this technique allows one to probe the structure of the K2V atmosphere, at spatial scales of about 10,000 km. As inferred from other techniques, much of the gas appears to be located far from the star, near the Keplerian co-rotation radius. Since the gas traces the magnetic field, this directly probes the magnetic field morphology. The lessons learned here should be directly applicable to the single URRs, pre-main sequence stars, and the RS CVn and BY Dra systems.

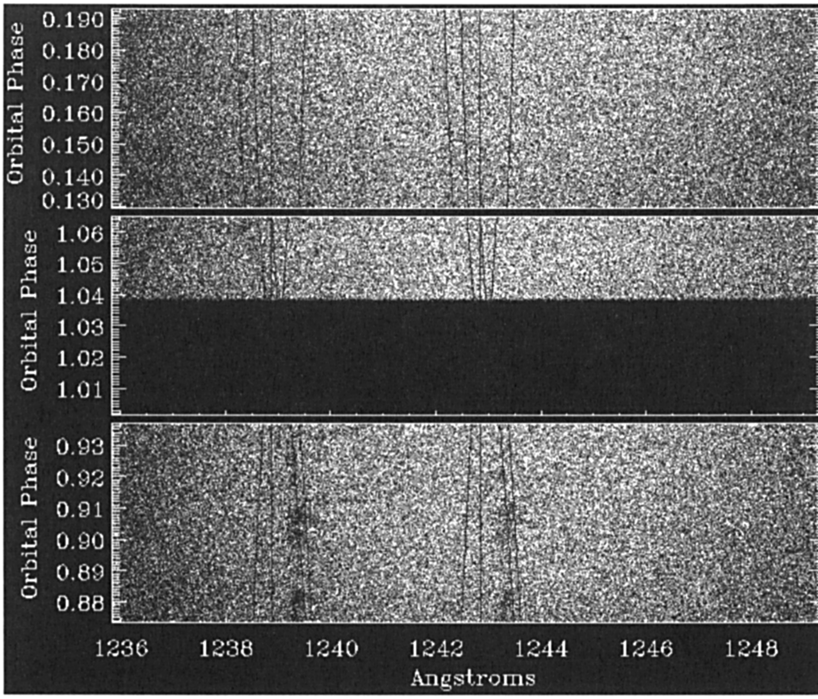

Figure 3. The time-resolved N V spectra during the CHANDRA observation. The absorption is weaker than during March 1998 (Fig. 1), and is seen prior to ingress rather than following egress. The thin lines show the velocities of (from left to right at ϕ=0.88) the K2V photosphere, the ISM, co-rotating gas, and the DA photosphere.

References

Bond, H.E., Mullan, D., O'Brien, M.S. & Sion, E.M. 2001, ApJ, 560, 919

Eaton, J.A. 1993, ApJ, 404, 305

Guinan, E.F., et al. 1986, in New Insights in Astrophysics: 8 Years of UV Astronomy with IUE, 197

Jensen, K.A., et al. 1986, ApJ, 309, L27

O'Brien, M.S., Bond, H.E., & Sion, E.M. 2001, ApJ, 563, 971

Ramseyer, T.F., Hatzes, A.P., & Jablonski, F. 1995, AJ, 110, 1364

Shipman H.L. et al. 1995, AJ, 109, 1220

Sion, E.M., Schaefer, K., Bond, H., Saffer, R., & Cheng, F. 1998, ApJ, 496, L29

Skillman, D.R. & Patterson, J. 1988, AJ, 96, 976

Walter, F. 1999, in ASP Conf. Ser. 158, Solar and Stellar Activity. Similarities and Differences, ed. C. Butler & J. Doyle (San Francisco: ASP), 87

Wheatley, P.J. 1988, MNRAS, 297, 1145