2001ASPC..223...29G

The 11th Cool Stars, Stellar Systems and the Sun
ASP Conference Series, Vol. 223, 2001
R. J. García López, R. Rebolo, M. R. Zapatero Osorio, eds.

Accretion Shocks and Winds in T Tauri Stars[1]

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Abstract. The dynamics of accretion and outflow in the T Tauri stars (TTSs) is expected to be associated with the production of shocks. Accretion shocks are expected to occur at the locations on the stellar surface where the kinetic energy of the infalling material is released into heating. Wind shocks are expected to be generated in the wind, at the base of the high velocity jets. Both types of shocks are expected to occur at velocities of some few hundreths of km/s and high densities ($> 10^6$ cm^{-3}) producing strong semiforbidden lines of O III], C III] and Si III] in the ultraviolet range. High resolution profiles of the Si III]$_{1892}$ and C III]$_{1908}$ lines are available for three pre-main sequence stars (AB Dor, RY Tau, RU Lup) in the IUE and HST Archives. In this contribution, evidence for shocks in the circumstellar environment of these sources is presented. In two out of the three cases studied, the shock is observed to occur in the wind, at the base of the optical jet. This is estimated to be at 0.2 AU from the base of the wind for RY Tau.

1. Introduction

Outflow is ubiquotous during star formation. Some basic models have been proposed to explain how this outflow may be driven (see Koenigl and Pudritz 1999, and Shu et al. 1999 for recent reviews). In these models the outflow is assumed to be powered by the gravitational energy released during the accretion process and the magnetic field is often hypothesized as the physical stress which efficiently channels the gravitational energy into the mechanical outflow energy. Determining the physical mechanism that connects accretion to outflow is one of the key issues in star formation since this regulates the accretion rate and the evolution during star formation. Moreover, it seems likely that the same physics applies to other astrophysical systems such as QSOs, AGNs or microquasars.

To obtain information about the physics of jet formation is necessary to go below scales of ~ 1000 AU down to angular sizes smaller than 0.1 arcsec (for the nearest star forming regions) which are not accessible to direct imaging. If the

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[1] Based on observations made with the International Ultraviolet Explorer (IUE) and with the NASA/ESA Hubble Space Telescope obtained from the HST data archive at the Space Science Institute, which is operated by the Association of Universities for Research in Astronomy Inc., under NASA contract NAS 5-26555

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density of the jet increases towards the source, the electron density at the base of the jet could be even higher than 10^6 cm^{-3} traced by the [O I]$_{6300}$ optical line. At these very high densities, the UV semiforbidden lines may be excited.

The C III]$_{1908}$ ($2s^2S_1$–$2s2p^3P_1$) and Si III]$_{1892}$ ($3s^2S_1$–$3s3p^3P_1$) UV intercombination lines are strong in the spectrum of the TTSs. A quick look at the IUE Final Archive shows that the Si III]$_{1892}$ line is detected in 21 stars and the C III]$_{1908}$ in 19 from a grand total of 36. Their detection was first reported for T Tau by Jordan et al. (1982); subsequent studies used these lines to derive the emission measure and model the structure of the atmosphere of the TTSs (see e.g. Gómez de Castro 1998 for a recent review). The ratio R=I(Si III]$_{1892}$)/I(C III]$_{1908}$) is density sensitive and it is often used to estimate electron densities in late-type stellar atmospheres within the range $10^8 \leq N_e \leq 10^{13}$ cm^{-3} (see Brown et al. 1984 for its application to T Tau). Recently, it has been shown that these lines could also be formed in accretion shocks (shocks where the kinetic energy from the material falling onto the stellar surface is released); the C III]$_{1908}$ and Si III]$_{1892}$ lines are expected then to be formed before the shock front where the infalling gas is ionized by the X-rays radiation produced in the hot (T$\sim 10^6$ K) post-shock region (Lamzin 1998; Gómez de Castro & Lamzin 1999). Particle density in the accretion column is typically between 10^{10} and 10^{13} cm^{-3}. Moreover, the C III]$_{1908}$ and Si III]$_{1892}$ lines could also be excited in dense shocks at the base of the jet where the material from a dense wind is collimated into a narrow beam of gas. In summary, these lines are an extraordinary diagnosis tool to study the major physical processes in the hot dense circumstellar environment around the TTSs.

In this contribution, high resolution profiles of the Si III]$_{1892}$ and C III]$_{1908}$ semiforbidden lines (SL) are presented for 3 pre-main sequence stars: AB Dor, RU Lup and RY Tau. The line emission from AB Dor seems to be caused in accretion shocks while in RU Lup and RY Tau there is evidence of the line being produced in a very dense wind at the base of the jet traced by the optical forbidden lines.

2. Archive data

The data were obtained from the International UV Explorer (IUE) and the Hubble Space Telescope (HST+GHRS) Archives.

The IUE high dispersion (R$\sim$ 10,000) data were obtained with an echelle spectrograph and a SEC integrating video camera as detector. The Si III]$_{1892}$ line is only clearly detected in RU Lup. Marginal detection of the Si III]$_{1892}$ feature can be claimed for T Tau (SWP15475) and RW Aur (SWP49878) (for more details, Gómez de Castro & Franqueira 1997, hereafter GF).

The HST-GHRS medium resolution (R$\sim$ 25,000) data were obtained with the first order grating G200M and the photon-counting Digicon detector D2. The Si III]$_{1892}$ and C III]$_{1908}$ lines were well centered in the detector which typically covered the 1880–1920 Å spectral range. The HST+GHRS have been processed using the IRAF/STSDAS package. The groups within a given data set have been aligned using the wavelength information provided with the calibrated HST data file and then co-added to produce the line profiles. The Si III]$_{1892}$ and C III]$_{1908}$

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lines are clearly detected in RY Tau and RU Lup. Only the Si III]$_{1892}$ line is detected in AB Dor.

3. Detection of accretion shocks: AB Dor

The Si III]$_{1892}$ profile of AB Dor is redshifted (see Fig. 1); the line centroid is at $\sim$ 50 km/s and the red-edge is at $V_r \simeq 100$ km/s, pointing out the presence of infalling gas. Emission from this infalling gas can also be tracked down in the Si II (UV1) high resolution profiles obtained with the IUE in April, 1983 (SWP19713). This velocity roughly corresponds to free-fall speed from 0.13 AU (or 30 $R_\odot$) and suggests that the star may be accreting cold gas from the environment. The presence of a low-mass companion (Guirado et al. 1997) may also have helped to keep some remnant material within this young stellar system and, in fact, the presence of redshifted absorption in Hα profiles has been reported for AB Dor and similar stars (Walter & Byrne 1998).

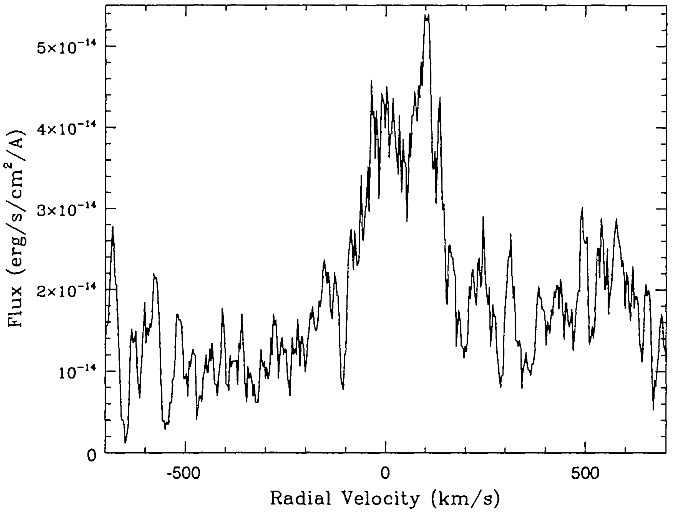

Figure 1. AB Dor Si III]$_{1892}$ profile plotted in velocity space.

4. Detection of wind shocks: RY Tau and RU Lup

4.1. RY Tau

The Si III]$_{1892}$ and C III]$_{1908}$ semiforbidden lines (SL) profiles are similar: asymmetric with the maximum blueshifted to radial velocity ~ -80 km/s (see Fig. 2; left panel). This profile is characteristic of lines formed in a wind and indeed, the high velocity component of the optical forbidden line of [O I] at 6300 Å, which is formed at the base of the jet, is at –79 km/s (Hamann 1994; Hartigan

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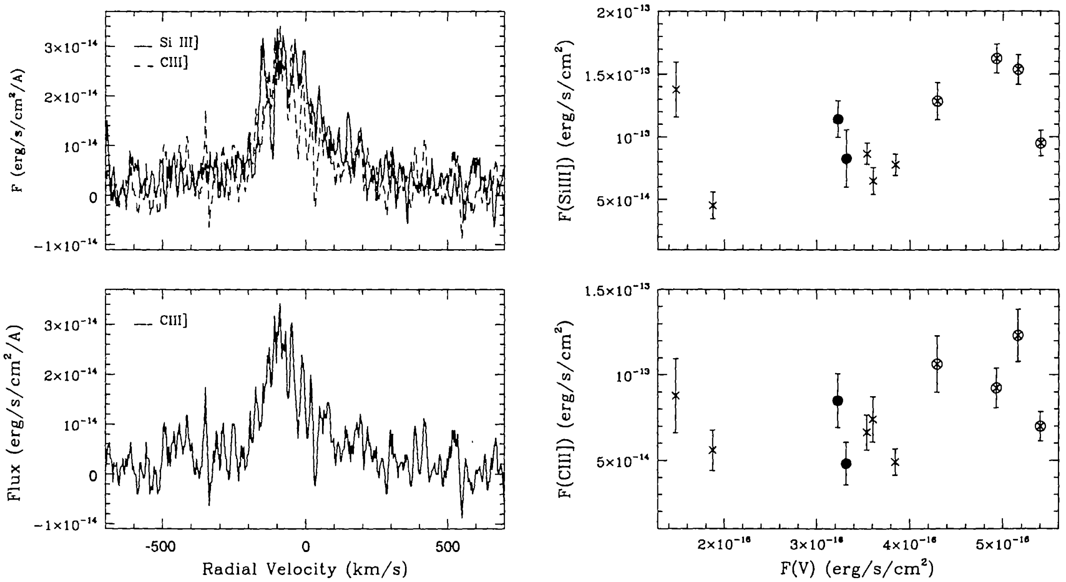

Figure 2. *(Left)* RY Tau SL profiles plotted in velocity space. *(Right)* Variation of SL fluxes with the optical flux derived from V magnitudes obtained with the IUE FES Camera; filled and open circles correspond to monitoring campaigns carried out in 1986 and 1989 respectively.

et al. 1995; Hirth et al. 1993). However, the [O I]$_{6300}$ line is significantly narrower (FWHM= 70 km/s) than the UV semiforbidden lines. High resolution long-slit spectra show no offset between the high velocity [O I]$_{6300}$ emission and the stellar position pointing out that this line forms within $\sim$ 42 AU of the star. Wind emission has also been detected in the optical forbidden lines of [Fe II] at 7155 Å and of [S II] at 6731Å.

RY Tau has been classified as an UX Ori star (UXor) or pre-main sequence star which shows aperiodic eclipse-like minima caused by variable obscuration by circumstellar dust (Grinin 1992). In this case, there should be a correlation between the line flux variations and the optical magnitude if the lines were formed very close to the stellar surface. RY Tau was observed with the IUE 14 times between 1979 and 1989 in the low dispersion mode (see GF for further information) and it is feasible to study this correlation because the visual magnitude was recorded at the begining of each UV observation (measured with the Fine Error Sensor (FES)). As shown in Fig. 2 (right panel) there is not correlation between the optical magnitude and the SL flux variations, therefore whatever is obscuring the star (protoplanet, circumstellar dust or accretion column or shell) is not obscuring the SL formation region. This, in turn, implies that this region must be further away than 1–2 R_* and discards its connection with accretion shocks (Lamzin 1999).

Neither the [C III]$_{1907}$ nor the [Si III]$_{1883}$ forbidden lines have been detected in the HST spectrum; this imposes a lower limit to the electron density of $N_e \geq 10^5$ cm^{-3} (Keenan et al. 1992). At this high electron density the [S II]

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doublet is collisionally depopulated which is also consistent with the very low strength of the [S II]$_{6731}$ line and the non-detection of the [S II]$_{6716}$ line.

The R=Si III]$_{1892}$ / C III]$_{1908}$ lines ratio is electron density sensitive at higher densities (Keenan et al. 1987); this ratio is equal to 1.1 ± 0.4 for RY Tau. Assuming ionization equilibrium (Arnaud & Rothenflug 1985) and using the theoretical predictions by Keenan et alx (1987), $\log N_e$ is derived to be ≤ 10.2. A more accurate determination of the density requires the use of detailed shock-excitation models for high density outflows (see Gómez de Castro & Verdugo 2000).

The profiles of the SL are significantly broader than those of the optical forbidden lines. The width of the UV lines is $\sim$ 200 km/s whereas the width of the [O I]$_{6300}$ line is just 70 km/s. This broad UV profiles cannot be produced in a narrow collimated beam of gas. The most likely source is emission from a bow-shock (a series of oblique plane shocks having as a consequence a range of velocities in the shock wave). Therefore, the UV lines are most probably formed in a bow-like shaped structure.

4.2. RU Lup

The Si III]$_{1892}$ and C III]$_{1908}$ line profiles of RU Lup are very different (see Fig.3, left panel). The Si III]$_{1892}$ line is strong and seems to be centered at at the stellar velocity. The line has a blue wing which extends up to radial velocity –300 km/s and the profile can be fitted by two gaussians:

1. A low velocity component with integrated flux equal to 2.1 $\times 10^{-13}$ erg s^{-1} cm^{-2} and centered at rest (within the wavelength calibration uncertainties). The Full Width Half Maximum (FWHM) of this component is 185 km/s.
2. A high velocity component with integrated flux equal to 7.6 $\times 10^{-14}$ erg s^{-1} cm^{-2} centered at –142 km/s. This component is very broad with FWHM=337 km/s.

There is a broad, weak emission feature at 2σ level at the location of the C III]$_{1908}$ line. This broad component seems to correspond well (in the velocity space) with the blueshifted component of the Si III]$_{1892}$ line. As in the case of RY Tau, this indicates that there is Si III]$_{1892}$ and C III]$_{1908}$ emission produced in the wind. In fact, the velocity of the blueshifted gas is similar to that of the base of the jet traced by the optical forbidden lines (see e.g. Haman 1994); this material is moving at ~ -140 km/s and it is detected in the [O I]$_{6300}$, the [S II]$_{4069}$ and in the [S II]$_{6731}$ lines. The UV lines are significantly broader than the optical.

There is also a narrow feature at $\sim$ 1907 Å which could be produced by a C III]$_{1908}$ line blueshifted by $\sim$ 240 km/s. This velocity corresponds also to the blue edge of the absorption component in the P-Cygni-like profile of the Mg II lines measured the same date with the HST+GHRS (see Fig. 4). Mg II profiles obtained 6 years before with the IUE show a much broader absorption than the observed in the HST data; the blue-edge moves to ~ -300 km/s surpassing the velocities at which the (presumably) C III]$_{1908}$ feature is detected. In consequence, the C III]$_{1908}$ feature could be well formed in the wind if, occasionally,

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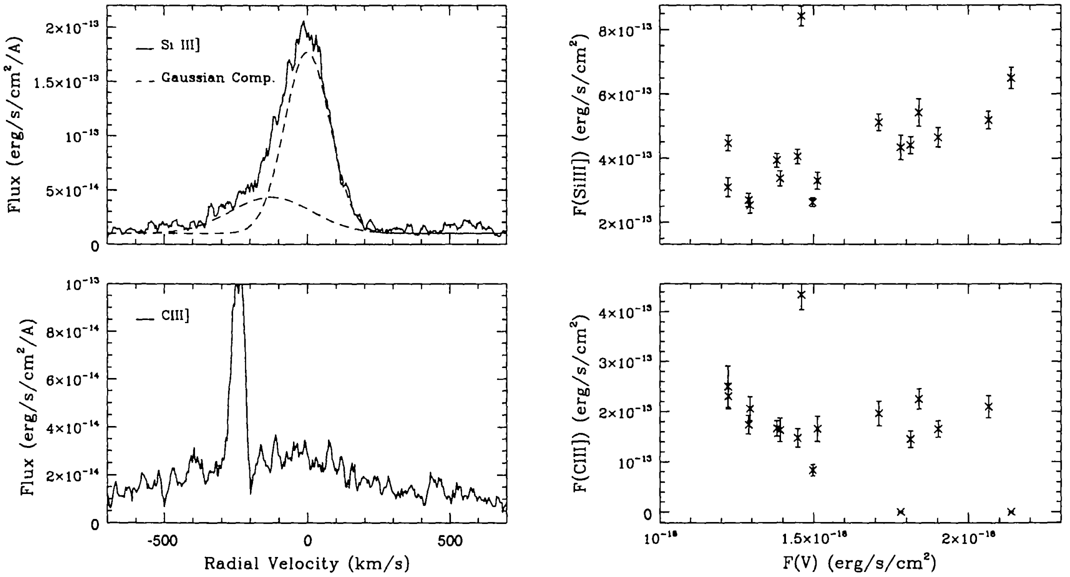

Figure 3. *(Left)* SL profiles of RU Lup; the Si III]$_{1892}$ profile (top panel) has been fitted by two gaussians centered at 0 and at –142 km/s which are represented by a dashed line (see text). Notice the presence of a narrow unidentified feature with velocity close to the Si III]$_{1892}$ profile blue-edge in the C III]$_{1908}$ profile. *(Right)* Variation of SL fluxes with the optical flux derived from V magnitudes obtained with the IUE FES Camera.

is heated up close to the terminal speed. The detection of a narrow feature in the C IV line at the high velocity edge of the C III]$_{1908}$ feature suggests that the wind may heat up as the velocity rises forming a shock at the terminal velocity of a warm dense wind. Further observations are instrumental to confirm this interpretation.

5. Discussion and conclusions

The detailed analysis of the RY Tau observations (Gómez de Castro & Verdugo 2000) shows up that the SL emission is most likely produced in a bow-like shaped structure located at a distance of $\sim 20R_*$ (or 0.2 AU) from the star and which has a radius of $\sim 8R_*$. This structure is assumed to be symmetric with respect to the disk axis and therefore, as the RY Tau system is seen close to edge-on, it is expected to produce the extended redwing observed in the SL profiles. These geometric constraints imply that there is a strong shock in the wind (where the SL lines are formed) within 0.2 AU from the star where the optical jet, traced by the [O I]$_{6300}$, is initiated. Such shocks are expected to be produced by the magnetic pinching (see e.g. Gómez de Castro & Pudritz, 1993) of centrifugally driven MHD winds which, in principle, may depart either from a disk or from a spheroidal structure. The shock is produced if the magnetic tension from the toroidal component is so strong as to recollimate (pinch) the flow back to the

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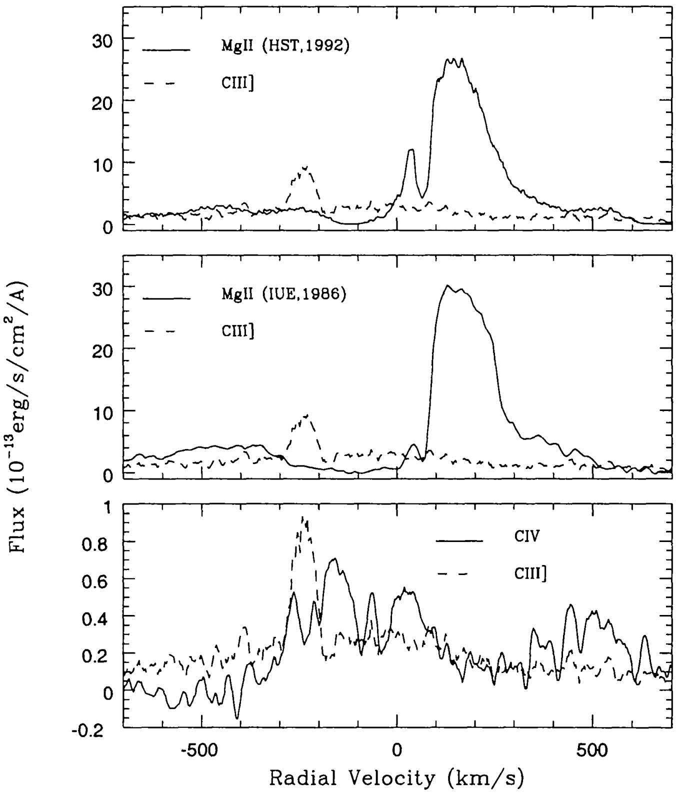

Figure 4. The C III]$_{1908}$ profile in 1992 (dashed line) is overplotted on the profiles of the Mg II (UV1) lines in 1992 (top panel), the Mg II (UV1) lines in 1986 (middle panel) and on the C IV (UV1) profile (1992).

axis at superalfvénic speeds. For MHD disk winds the location of the shocked surface is expected to occur at a distance of the source D given by:

$$D = 9.6 \times R$$

where R is the radius of the flow; the fiducial values used above are the same as described in Gómez de Castro & Pudritz (1993). This equation predicts that if the shock is produced at a distance of some 10–20 R_* from the source of the wind the radius of the wind must be 1–2 R_*, it means, a stellar or magnetospheric wind but not a large scale (R=2AU) disk wind. In practice, these data do not rule out disk-wind models since the refocussing distance (D) was calculated using an asymptotical approach (Pelletier & Pudritz, 1992) which, in turn, implies very large (and possibly unrealistic) Mach numbers. In fact, the presence of shocks can be tracked down also in the recollimating set of polytropic self-similar solutions described by Contopoulos & Lovelace (1994) and in some of the complete set of self-similar solutions described by Vlahakis & Tsinganos (1998). In these solutions the shock is expected to be produced very close to the fast magnetosonic point (the point where the wind velocity equals the total Alfvén velocity) and this point is significantly closer to the source of the wind.

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The SL fluxes are variable; there are 21 low dispersion observations of RU Lup available in the IUE Final Archive (see GF). The Si III]$_{1892}$ variability is correlated with the optical while the C III]$_{1908}$ is not (see Fig. 3; right panel). The correlation between optical (V-band) and the Si III]$_{1892}$ flux points out that most of the Si III]$_{1892}$ emission is associated with the star. This provides further confirmation on the association of the the low velocity component with the star. However, the C III]$_{1908}$ flux has remained approximately constant and has not varied with the optical flux suggesting that the C III]$_{1908}$ line is not emitted on the stellar surface.

Acknowledgments. I thank Constantino Ferro Fontán, Eva Verdugo and Sergei Lamzin for insightful conversations and Ilana Dashevsky from the Spectrographs Group (STScI) for her assistence in the interpretation of the GHRS data. This research was supported by the MEC through grant PB97-267.

Discussion

J. Linsky: There is a forbidden line of C III]$_{1908}$ at about 1907 Å. The –267 km/s component of the C III]$_{1908}$ line in RU Lup could instead be the [C III]$_{1907}$ line that is formed at low density?

A. I. Gómez de Castro: The ratios between the intercombination and the forbidden components of the C III]$_{1908}$ and Si III]$_{1892}$ multiplets are similar within a broad range of electron temperatures (5000K–20,000K) and densities ($10^2 - 10^6$ K) (Keenan et al 1992). Therefore, should the forbidden component of the C III]$_{1908}$ multiplet be detected, also the forbidden component of the Si III]$_{1892}$ multiplet should be detected which is not the case. Therefore, this identification is unlikely.

A. Collier-Cameron: The downflow speeds of $\sim$ 50 km/s you report in Si III]$_{1892}$ for AB Dor are comparable with absorption velocities seen in Hα in various other similar stars, e.g. BD+22 4409. Could you be seeing failed prominences that have condensed in a region where no stable mechanical support is available?

A. I. Gómez de Castro: Further observations are clearly required but, if the overall shape of the profile is confirmed, this would indicate that there is a fair fraction of the material falling at velocities as high as 100 km/s which correspond to free-fall speeds from 30 $R_\odot$. The *apparent* presence of two components at 0 and 100 km/s is also suggestive of the presence of shocks.

J. Schmitt: Could you elaborate on why you think there are accretion phenomena in AB Dor?

A. I. Gómez de Castro: AB Dor is a very young star and there could be some left-over material nearby the star which is naturally falling onto the stellar gravitational well.

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2001ASPC..223...29G

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