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EXPLORING THE CENTRAL ENGINES OF YOUNG STARS

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RESUMEN

Para entender los orígenes de los jets de líneas de emisión de estrellas jóvenes, tenemos que investigar sus ambientes circunestelares inmediatos a escalas de 10 UA o menos. Aunque esto es difícil de hacer en fuentes altamente embebidas, fuentes de flujos ópticamente visibles, tales como las estrellas T Tauri clásicas y estrellas Herbig Ae/Be, a veces nos ofrecen una ventana hacia sus "máquinas centrales". Aquí, en particular las líneas de emisión prohibidas son un diagnóstico extremadamente útil. Por ejemplo, en ellas se pueden ver diferencias mayores en las condiciones de excitación, velocidad, ángulos de apertura, y así sucesivamente, entre los jets opuestos cerca de su fuente. Además, en la fuente no solo observamos emisión de alta velocidad (del jet), sino también flujos de baja velocidad que se mueven a velocidades cercanas a la sistémica de la estrella. El origen de esa emisión de baja velocidad sigue siendo controversial. Aquí revisamos brevemente descubrimientos recientes en esta área usando imágenes de *HST* y espectroscopía, como también observaciones espectro-astrométricas terrestres. El flujo óptico de DG Tau se usará como un ejemplo y observaciones recientes de *HST* se examinarán en el margen de los modelos actuales.

ABSTRACT

If we are to understand the origins of emission line jets from young stars we have to probe their immediate circumstellar environments on scales of 10 AU or less. Although this is difficult to do in the case of highly embedded stars, optically visible outflow sources, such as classical T Tauri stars and Herbig Ae/Be stars, sometimes offer us a window on their "central engines". Here in particular forbidden emission lines are an extremely useful diagnostic. Major differences, for example, can be seen in excitation conditions, velocity, opening angles, and so on between jets and counterjets close to their source. Moreover, at the source we observe not only high-velocity (jet) emission but also lower-velocity outflows moving at speeds close to the systemic velocity of the star. The origin of this low-velocity emission remains controversial. Here we briefly review recent findings in this area using *HST* imaging and spectroscopy as well as spectro-astrometrical observations from the ground. The optical outflow from DG Tau will be used as an example and recent *HST* observations of this young star will be examined in the light of current models.

Key Words: **ISM: HERBIG-HARO OBJECTS — ISM: JETS AND OUTFLOWS — LINE: FORMATION — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

It is over two decades (e.g., Ray 1996) since the discovery of outflows from young stellar objects (YSOs). On the theoretical front we have made enormous progress in understanding the interaction of YSO outflows with their environments on scales of several thousands of AU. In large part this has been possible because of the increasing sophistication of numerical simulations (see, for example, Frank, Gardiner, & Lery 2002 and O'Sullivan & Lery 2002) aided by a wealth of observations at a variety of wavelengths. At the same time little is known about the "central engines" of YSOs in the sense that we still do not know precisely how outflows are generated. Here we are as much in the dark as our AGN colleagues! There is nevertheless a general consensus that outflows are somehow centrifugally launched along open magnetic field lines which might originate in the disk (the so-called disk wind model, e.g., Königl & Pudritz 2000) or from the YSO itself (the X-wind model, e.g., Shu et al. 2000). Observational evidence for magnetic fields in outflows however is rare and it seems impossible, for example, to estimate magnetic field strengths from line ratios (Hartigan, Morse, & Raymond 1994). That said there is some direct (Ray et al. 1997) and indirect evidence (Morse et al. 1992) that they may be dynamically important.

As with their larger extragalactic brethren, the biggest problem in probing how YSO jets are accelerated and collimated is the difficulty in resolving the relatively small scales over which these processes occur. For example, if one assumes, as a first approximation, that a YSO jet is accelerated in a distance

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$D_{\rm acc}$ determined by the depth of the gravitational potential well from which it forms:

$$D_{\rm acc} \approx GM_\star/{V_{\rm jet}}^2,$$

then, for Herbig-Haro type jets (with $V_{\rm jet} \approx$ 200–300 km s^{-1}), $D_{\rm jet}$ should be around 0.01 AU i.e., close to the surface of the star. At the distance of the nearest star forming regions, such as Taurus-Auriga or Ophiuchus, we would need milliarcsecond or better resolution to see the jet being launched. Clearly this is something which is beyond current instrumentation but hopefully achievable with the next generation of optical/near-infrared interferometers like AMBER/VLTI. Of course such small scales represent an extreme view: for example, models which invoke centrifugal acceleration achieve high poloidal velocities through a lever-arm effect (see, for example, Königl & Pudritz 2000). Thus velocities at the base of the flow, where the jet is launched, may only be a small fraction of their terminal values. The acceleration/collimation scales are correspondingly larger although still too difficult to resolve using current ground-based instrumentation. Another problem one would have to face, even if optical/near-infrared interferometers were available with such resolution, is the very high extinction values towards many YSOs. Fortunately, a number of classical T Tauri/Herbig Ae/Be stars are associated with Herbig-Haro (HH) jets and in these cases the source is *usually* seen directly at optical wavelengths. The term 'usually' is used here because in some cases, e.g., HL Tau (Stapelfeldt et al. 1995), we may not be observing the source directly but instead a reflection nebula. Of course classical T Tauri and Herbig Ae/Be stars are evolved YSOs, typically with Class II IRAS spectra, and their outflows tend to be less powerful than those from more highly embedded YSOs of comparable mass. The jets from, for example, CW Tau and DG Tau (Dougados et al. 2002) look a lot less dramatic than those from HH 34 IRS or HH 111 IRS. Such flows are (somewhat disparagingly!) referred to as "micro-jets" (Solf 1997) as they may appear to extend only a few arcseconds. Their study, however, is critical, because of the window they offer us on the engine itself, if we are to obtain clues as to how jets are generated.

Rather perversely, the fact that the source is optically visible is something of a "mixed blessing"! In particular strong light from the YSO can cause a contrast problem when trying to observe the relatively faint outflow close to the star. Although the problem is somewhat eased when imaging with narrow-band filters, even they do not isolate outflow lines well enough to sufficiently suppress the background continuum. As the emission line widths of HH flows/jets are typically around 100 km s^{-1}, the solution, if we want to obtain optimum S/N for the outflow, is obviously long-slit spectroscopy at intermediate dispersions or, alternatively, Fabry-Perot type imaging. The advantage of the former, in comparison to the latter, is of course that many lines can be observed simultaneously. Although the field of view is somewhat restricted when using long-slit spectroscopy, when compared to an FP system, nevertheless this is compensated for by the fact that, by and large, outflows are 1-D![3]

The study of forbidden emission line (FEL) regions in classical T Tauri stars has a long and venerable history (for example see Hartigan, Edwards, & Gandhour 1995 and references therein). Early observations often showed the presence, in individual lines, of two or more velocity components. Usually only blueshifted components were seen and, in the simplest cases, one could identify emission close to the systemic velocity of the star (the so-called low velocity component or LVC), as well as a high velocity component (or HVC). As the HVC had typical velocities similar to those of the more extended jets, i.e., up to several hundred km s^{-1}, this component was immediately recognised as the unresolved jet close to the star. The apparent velocity asymmetry in the lines, i.e., lack of redshifted emission, was then ascribed to obscuration of the counterflow by a disk (on sub-arcsecond scales). The origin of the LVC was less clear. This component was typically broad (δV $\approx$ 100 km s^{-1}) and early efforts at modelling it attempted to understand both components in terms of a poorly collimated wind viewed at arbitrary angles to the outflow direction (e.g., Edwards et al. 1987; Safier 1993). The fits to the observations however were very poor and such geometric models were quickly abandoned. An alternative scenario, put forward by Kwan & Tademaru (1988) sought to explain the LVC as a poorly collimated disk wind with a separate origin for the jet (HVC). Here the broadness of the LVC was attributed to rotation of the disk. As the LVC was seen to peak near the systemic velocity of the star, more emission had to come, according to this model, from the periphery of the disk (where the rotation velocities are lowest) rather than the centre (Kwan & Tademaru 1995). According to this scenario, the wind is generated by magnetic torque in the disk.

[3]As we will show this advantage is less obvious at *HST* type resolutions where one starts to resolve the flow, even close to the source, in the transverse direction.

Support for the idea that the LVC and HVC are two *physically* separate regions near YSOs came from a number of sources. For example observations using various emission line diagnostics suggested the density and excitation conditions of the LVC and HVC were different (e.g., Hamann 1994; Hartigan et al. 1995). The LVC was seen to typically be of higher density and lower excitation than the HVC. Studies of both components close to young stars were greatly aided by the development of spectro-astrometric imaging by pioneers such as Karl-Heinz Böhm and Josef Solf (Böhm & Solf 1994). This technique involved the use of long-slit spectroscopy and, after careful subtraction of the stellar continuum, one was left with a "pure" emission line spectrum that served as a two-dimensional position-velocity map. At the same time the relative positions of the star and centroids of emission could be determined to an accuracy which was in principle a function of the S/N ratio in the absence of any systematic errors. Using this technique Hirth, Mundt, & Solf (1997), through studies of the nearest star forming regions, have shown not only that the HVC is extended, on scales of a few tenths of arcseconds, in the outflow direction but that the LVC is very compact and, at best, marginally resolved (see also Takami et al. 2001). Another interesting property of the LVC is that it shows a clear inverse correlation of velocity with forbidden line critical densities. This has been interpreted as evidence of acceleration in the LVC with distance from the star (Hirth et al. 1997).

Although the HVC and LVC have distinct physical properties, it is found that their strengths are nevertheless correlated (see Fig. 7 in Calvet 1997). The relationship is not linear, however, in that the LVC becomes dominant at low line luminosities.[4] Of course, just because the intensity of the LVC and HVC are correlated it does not mean that they have the same origin. Both ultimately are powered by accretion, which is the primary arbiter of their strength (see, for example, Corcoran & Ray 1998a).

Let us now turn briefly to the HVC on somewhat larger scales: where it is first resolved from the ground as a jet. In a number of stars of the type we have described, for example, the T Tauri star RW Aur (Hirth et al. 1997; Dougados et al. 2000) or the Herbig Ae/Be star LkHα 233 (Corcoran & Ray 1998b), bipolar jets are seen close to the star. Normally, of course, the blueshifted emission is brightest but what is striking is that there can be major differences between the flow/counterflow which cannot be ascribed to extinction effects alone. These include asymmetries in absolute jet velocity, apparent opening angle of the flow, electron density, excitation as well as morphology. Although it is not clear how such asymmetries arise, it is likely that differences in the immediate stellar environment probably play a major role in their production. The asymmetries between the flow and the counterflow, as we have said, can be quite large, for example a factor of two in velocity is not uncommon (Eislöffel et al. 2000).

Since the ground-based studies point to LVC regions having dimensions of a few tenths of an arcsecond for nearby YSOs, and given that the HVC (as seen from ground-based observations) should be resolvable into a jet, optically visible YSOs are obviously ideal targets for *HST* . With these ideas in mind, we have begun a study, using the Space Telescope Imaging Spectrograph (STIS) of a small number of optically visible YSOs (DG Tau, RW Aur and LkHα 233). Initial results for the case of DG Tau have already being reported in the literature (Bacciotti et al. 2000) while a more detailed analysis is currently in preparation (Bacciotti et al. 2002). Observations of the other stars have been completed recently and are currently being studied. Here we describe some of our results in the immediate vicinity of DG Tau, a source which has featured prominently in this meeting (see, for example, the contribution by Dougados et al. 2002).

Historically, DG Tau was one of the first young stars from which a HH jet (HH 158) was discovered (Mundt & Fried 1983). Ground-based studies (e.g., Lavalley et al. 1997), and even early (uncorrected) *HST* imaging observations of this star have been made (Kepner et al. 1993). The jet on large scales (around $10''$) *appears* to terminate in a bow-shock (Eislöffel & Mundt 1998) and smaller bow shocks are also seen closer to the star (see the *HST* Archive images in Figure 1). The actual technique we employed to "image" the emission line region of DG Tau is described in detail elsewhere (Bacciotti et al. 2000). It suffices here to say that we stepped the STIS slit in the transverse direction to the outflow with a small enough offset to sample the *HST* point spread function (albeit not quite at the Nyquist limit). A total of 7 spectra were taken which were subsequently merged together (for individual lines) to produce a flux density/radial velocity data-cube. In this way we built up "images" of the emission line region in different velocity bins and for a range of diagnostic lines. Note that all quoted velocities in subsequent

[4]Incidentally, this suggests that in those (presumably evolved) T Tauri stars where only an LVC has been observed, there are hidden jets (HVCs). Perhaps these can be spectroscopically revealed using 8/10 m class telescopes.

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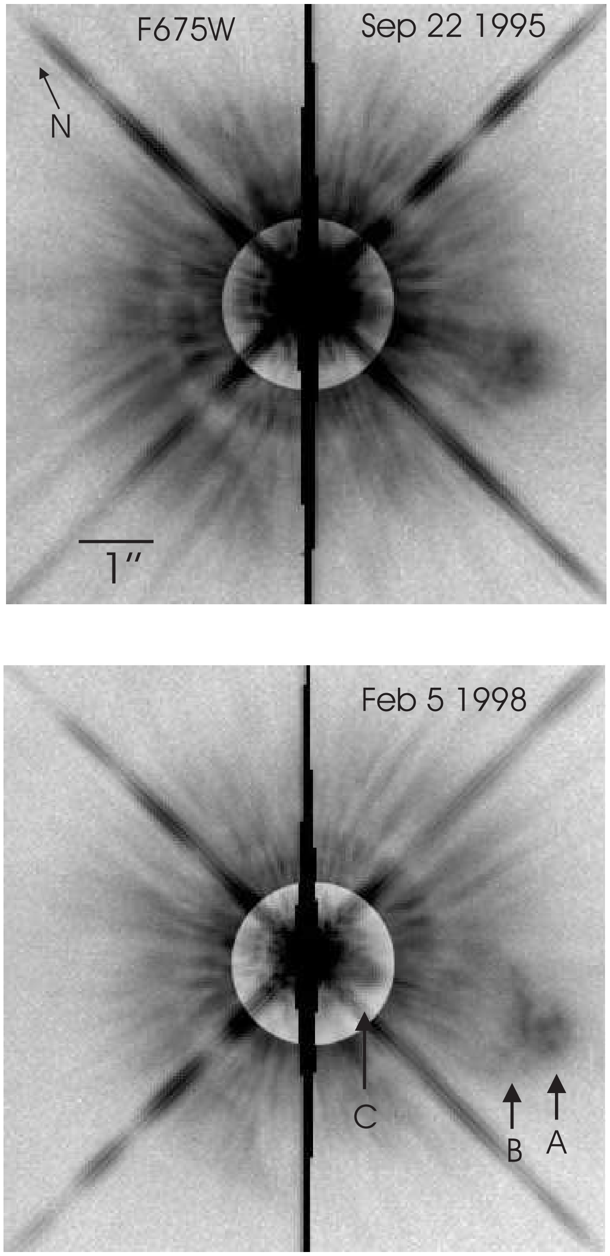

Fig. 1. Two images from the *HST* Archive of the DG Tau outflow taken 2.6 years apart using a broadband red filter. The region within 1.″0 from the star is shown at higher contrast. The outflow can be seen to the lower right. Note the proper motion in its knots, the alteration in their structure and the emergence of a new, bowshock-like, feature (C) close to the source in the 1998 image. Archive data is from programs 6223 and 6855 (PI: J. Trauger).

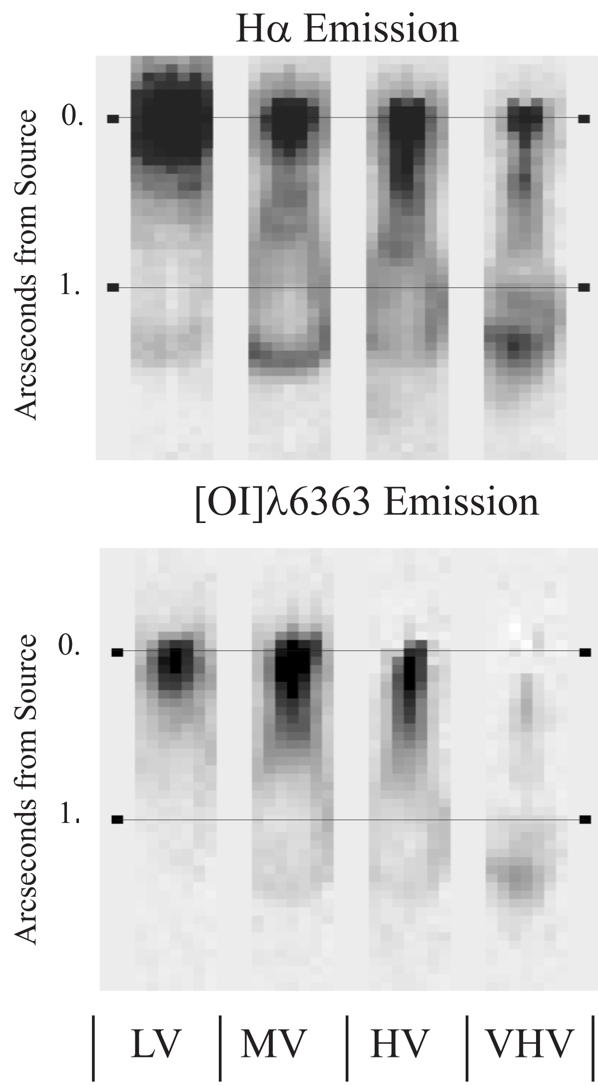

Fig. 2. Synthetic images of the DG Tau outflow in Hα and [O I] λ 6363 derived from 7 overlapping long-slit positions offset in the transverse direction to the flow. Four broad velocity bins are shown: low (LV), medium (MV), high (HV) and very high (VHV) covering the range +50 to −450 km s^{-1} and each bin having an approximate width of 125 km s^{-1}. The outflow appears to broaden i.e., become less collimated as the velocity decreases. The lowest velocity emission however does not extend far from the star (a few tenths of an arcsecond at most) consistent with the ground-based observation that the LVC appears compact. The curved bowshock beyond 1″ is almost certainly the new ejection event identified as C in Fig. 1

figures are systemic using $V_{\star,\rm hel} \approx +16.5$ km s^{-1}, as derived from the Li λ 6707 photospheric absorption line.

The first thing that strikes one when looking at the images (see Figure 2) is the remarkable way in which the outflow changes in appearance at different velocities and in different lines. Looking at the region closest to the star (i.e., within 0.″5) we see that, at the highest velocities, the jet is narrowly confined to the central axis of the outflow and to be unresolved in its transverse direction. With decreasing velocity the outflow appears to broaden and to become less collimated. This low velocity emission however does not extend far from the star (a few tenths of an arcsecond at most) consistent with the ground-based observation that the LVC appears compact. Note, however, that these are the first observations to resolve the LVC in the *transverse* direction to the flow.

One very interesting finding is that whereas we can trace the high velocity jet right back to the star in a permitted line like Hα, the emission seems to peter out in the case of, for example, [O I] $\lambda\,6363$ and to be virtually absent (at the highest velocites) in [S II] $\lambda\lambda\,6716, 6731$. The obvious reason for this (Bacciotti 2002) is that the electron densities are close to, or higher, than the critical values for these lines. On the other hand, at lower velocities we can detect emission in these forbidden lines right back to the source. This suggests that not only are we seeing evidence for an increase in density with proximity to the star along the outflow direction but also of *an increase in density with velocity, i.e., in the lateral as well as the longitudinal direction to the flow.*

Perhaps, however, one of our most interesting findings is the tentative evidence (at low velocities) for rotation in the flow from DG Tau. These findings are discussed more fully in Bacciotti et al. (2002) and here we only sketch our results. We first suspected that there might be evidence for rotation in the forbidden lines when the lowest velocity emission was more finely rebinned. To test this idea further, we divided the jet along the flow direction into four domains of increasing distance from DG Tau. We shall refer to these domains as Regions I, II, III, and IV corresponding to 0.″025–0.″125, 0.″125–0.″225, 0.″225–0.″325, and 0.″325–0.″475 from the source, respectively. Emission within these domains was binned along the slit for each of the seven slit positions. Our results are presented in Figure 3 where we have plotted the the difference in peak LVC velocity between corresponding slit pairs, i.e., S1 − S7, S2 − S6, and S3 − S5. Here slit S4 corresponds to the central slit position, S1 is to the southeast of the jet and S7 to the northwest. The offset in the slit positions is 0.″07, corresponding to about 10 AU at the distance of DG Tau. We see that in all regions from the star (I, II, III, and IV) the value of the velocity shift is almost always *negative*, for any line and for any "position pair". Put another way, the southeastern side of the jet moves towards the observer faster

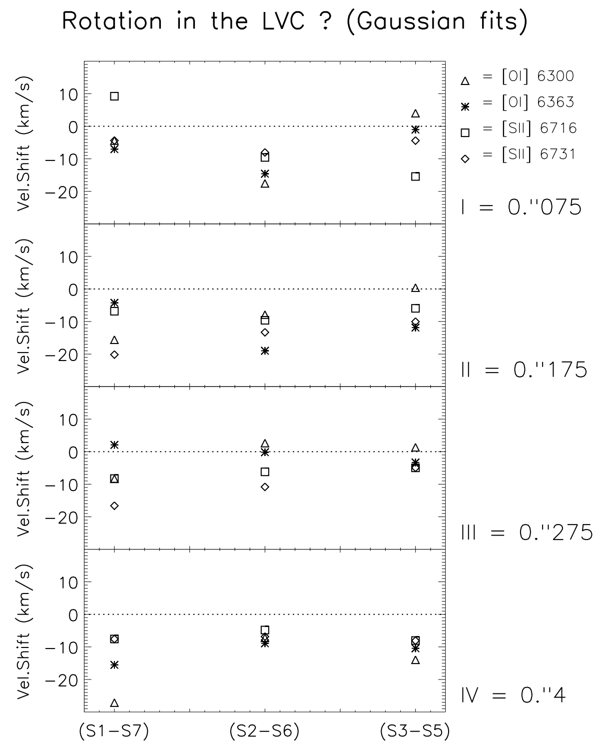

Fig. 3. This figure shows possible evidence for rotation in the low velocity outflow component in DG Tau. Using gaussian fits to the peak line profiles, the *difference* in velocity between corresponding slit pairs (i.e., equidistant from the outflow axis) is plotted for the various regions defined in the text. Symbols are used to represent different lines. Allowance has been made for uneven illumination of the STIS slit. Note how virtually all velocities are negative suggesting a net rotation.

then the corresponding northwestern side. The average value found for the shift is about 10 km s^{-1}. If we interpret these findings in terms of *rotation of the flow*, they would imply that the jet is rotating clockwise looking from the flow towards the source. Taking into account the inclination of this system with respect to the line of sight, the apparent linear azimuthal speed at a few tens of AU from the axis, and between 30 to 50 AU above the disk plane, is about 10 km s^{-1}.

There are a number of possible sources of systematic errors which might mimic the effects of rotation including uneven illumination of the STIS slit. However, as far as we can tell these have either being removed or are not important (see Bacciotti et al. 2002 for a comprehensive discussion of this topic). A further point is that Gaussian fitting to the peak LVC

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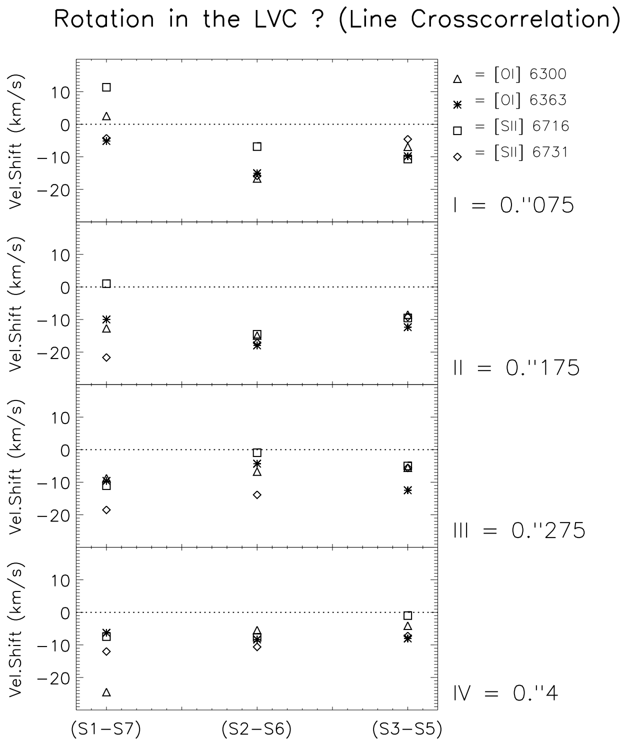

Fig. 4. As in Fig. 3 but using a line cross-correlation technique as oppossed to gaussian fitting. The results are broadly consistent with those in Fig. 3

velocities may not be appropriate giving the complex nature of the observed line profiles. To test whether this might be the case we (Bacciotti et al. 2002) also carried out a cross-correlation fit to the lines. As seen in Figure 4, the results were almost identical to those from the Gaussian fitting procedure. Although confident that we have found tentative evidence for rotation, it would consolidate this finding if similar results were seen in our remaining *HST* targets. Finally we should mention that there has been another claim that rotation may have been observed in the outflow from a star, although on much larger scales than those discussed here: Davis et al. (2000) in a kinematical study of the H_2 knots in HH 212 have observed what may be a net rotational motion in addition to the large forward motion detected in the system (see also Chrysostomou 2002).

Assuming then we can interpret the lateral asymmetry in outflow velocity in terms of rotation, are the observations consistent with what might be expected on the basis of current MHD models (see, for example, Königl & Pudritz 2000; Camenzind 1997; Shu et al. 2000; Ferreira & Pelletier 1995; Shibata & Kudoh 1999), all of which invoke centrifugal forces to launch the jet? If the magneto-centrifugal scenario is correct, the flow should conserve its angular momentum, once it has reached terminal values. Naively one might expect, given the typical lever arm sizes predicted by these models, azimuthal velocities of roughly the magnitude observed at distances of 10–20 AU from DG Tau. Unfortunately, in the literature, many of these models have concentrated on deriving poloidal velocities as a function of distance and on understanding the highest velocity component. It would seem, however, there is a urgent need to better model the peripheral regions of the outflow as these are the ones we are beginning to resolve!

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