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# Unveiling the Role of Jets in Star Formation

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**Summary.** We describe the role of HST in providing the first and long-awaited observational backing for the role of bipolar jets in the star formation process.

## 1 Introduction

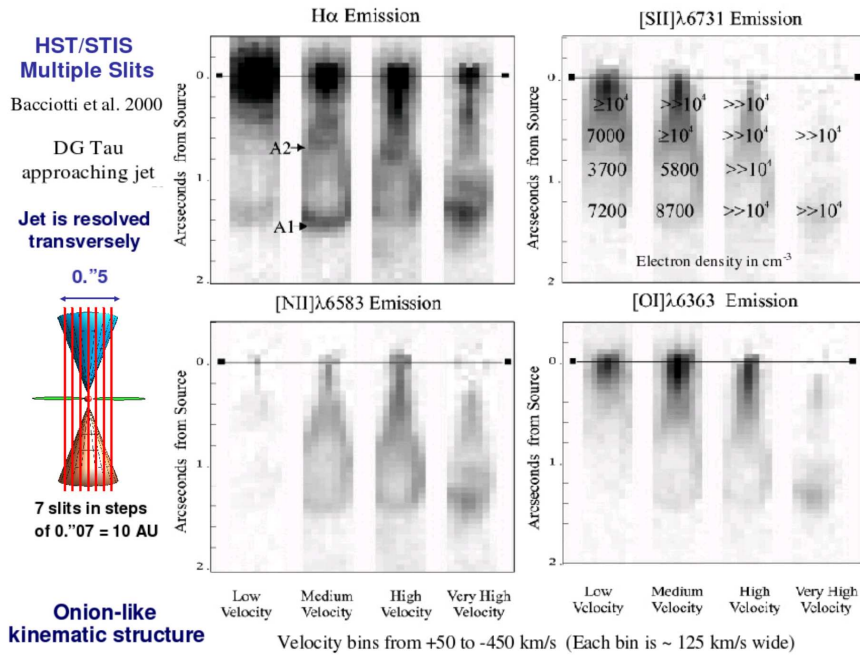
The striking phenomena of jets/outflows from protostars and pre-main sequence stars was wholly unanticipated by theorists, who are still striving to understand the basic mechanisms involved. Progress is hindered by long-standing observational difficulties due to small spatial scales, and the fact that many such objects are heavily embedded.

For example, proper motion studies of outflows, at the resolution of standard non-AO ground-based telescopes, demand relatively long time intervals between observations ( $\sim 5$  years for the nearest objects). Meanwhile, the outflow from XZ Tau observed with *HST*/WFPC2 at one-year intervals exhibited dramatic changes on such timescales. These observations allowed measurements of outflow velocity *and deceleration*, and revealed an extraordinary brightening of the star itself in rarely observed EXor-type fashion [1]. Furthermore, given that jet widths are typically about  $1''$ , ground-based non-AO observations cannot attempt to differentiate between models currently proposed for jet generation. However, *HST*/STIS spectroscopic observations, of more evolved (and hence less embedded) optically visible pre-mainsequence stars, allow detailed analysis of the jet internal structure and kinematics and, as a result, have contributed significantly to our understanding of the the role of jets in the star formation process, Sect. 2 and 3.

## 2 Determining Jet Mass Flux

Given that supersonic jets and outflows are observed to transport significant amounts of energy and momentum away from the central source, the most important parameter in any outflow model is mass flux. This requires a

knowledge of the total gas density, which is not directly measurable. However, the electron density can be easily obtained from the [S II] $\lambda\lambda 6718,6731$  doublet, and the ionisation fraction can be found using a technique developed in recent years to determine jet physical conditions by comparing optical forbidden emission line ratios [2]. Hence the total density can be obtained. This technique was applied to jet observations using a *HST*/STIS multiple-slit configuration. The resulting 3-D datacube allowed extraction of 2-D images for given velocity intervals, Figure 1. These revealed an onion-like kinematic structure, in which the gas is more collimated at higher velocities and excitations [3] [4]. From these maps, emission line ratios then give information about the gas physics [5]. For example, the electron density is higher closer to the star, closer to the flow axis, and at higher velocities. At the jet base, the temperature is  $8 \cdot 10^3 - 2 \cdot 10^4$  K, and the ionisation fraction is 0.01 - 0.4 yielding a total gas density of  $\sim 10^6 \text{ cm}^{-3}$ . From these values, the initial mass flux in the jet,  $\dot{M}_{\text{jet}}$ , is found to be of the order of  $10^{-7} M_{\odot} \text{ yr}^{-1}$ , with the colder and slower external layers contributing most. According to magneto-centrifugal models,  $\dot{M}_{\text{jet}}$  should be about 5 - 10% of the mass accretion rate through the disk onto the central object. These observations confirm this prediction in all the cases studied.



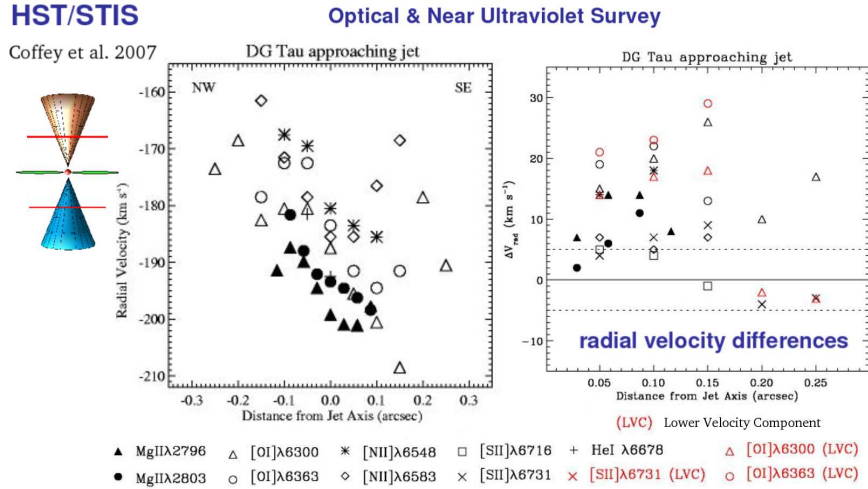
**Fig. 1.** HST/STIS observations allowing the jet to be resolved transversely and providing a 3D datacube from which 2D channel maps in different velocity bins could be obtained.

### 3 Indications of Jet Rotation

Collimated jets are believed to extract a substantial amount of the excess angular momentum from the star/disk system, thus allowing disk accretion. Several models propose apparently feasible mechanisms of jet launching [6] [7] but, since this occurs within a few AU of the star, the observational evidence favouring one model over another has remained elusive.

In recent years, a new parameter for constraining theoretical models has emerged facilitated only by the high angular resolution of *HST*, namely indications of *rotation* of jets about their symmetry axis. This interpretation followed from the detection of systematic radial velocity differences of typically 10 - 25 km s<sup>-1</sup> across the jet in *HST*/STIS optical and near-ultraviolet spectra, Figure 2, [8] [9] [10] [11]. These studies constitute a survey of eight jets, and reveal that transverse gradients in Doppler shift are common among these objects. Furthermore, in the two cases where both lobes of the bipolar jet were observed, there is agreement in the sense of Doppler gradient, as would be expected from a rotating bipolar flow. There is also agreement in measurements made at optical and near-ultraviolet wavelength ranges, and there is agreement in results for the two cases observed with both parallel and perpendicular slit configurations. Finally, there is agreement in the sense of Doppler shift between the *jet and disk* in two of four cases observed (i.e. DG Tau [8] [12], and CW Tau [9] [13]), a further one case remains inconclusive (i.e. HH 30 [9] [14]), and a fourth case shows a disagreement (i.e. RW Aur [9] [15]), although this latter case is a complex triple system showing evidence of tidal-stripping and so unidentified influences could be coming into play. An alternative explanation for a gradient in radial velocity across the jet base could be the presence of asymmetric shocks or jet precession, but these explanations are less likely [11]. Nevertheless, it is important to build the survey sample, especially in terms of agreement between jet and disk.

A number of theoretical analyses have subsequently demonstrated the implications of interpreting measured Doppler gradients as jet rotation. That is, when combined with other jet parameters, measured radial velocities differences allow the extraction of important information such as the jet launching radius, under the assumption of steady magnetohydrodynamic ejection [10] [16] [17] [18]. The results consistently show that, at the resolution of the observations, the jet is launched from a region of 0.1 - 4 AU from the star on the disk plane. Therefore, if indeed the detected Doppler gradients trace rotation within the jet then, under the assumption of steady MHD ejection, the derived footpoint radii support the existence of magnetized warm disk winds [18]. However, since we do not resolved the innermost layers of the flow, we cannot exclude the possibility that there also exists a stellar wind [6] or an X-wind [7] component. Importantly, the implied jet toroidal velocities cannot be explained by an X-wind model alone, nor by a cold disk-wind [18]. Although we cannot probe the inner axial part of the flow at the current resolution, this may be possible in the near future via interferometry.



**Fig. 2.** HST/STIS observations of gradients in Doppler shifted radial velocities across the jet base, indicative of jet rotation close to the launching point.

Combining measures of jet toroidal velocities with jet mass flux allows an estimate of the total amount of angular momentum flux of the jet for the observed region. Calculations show that the jet can extract 60-80% of the excess angular momentum the disk needs to lose in order to accrete onto the star [10] and hence determining observationally for the first time that the jet's role in the star formation process is a considerable one.

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