# STAR FORMATION AND BIPOLAR FLOWS

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Observations of molecular outflows from regions of star formation show that they cannot be radiatively driven ($(\dot{M}v)_{mol} \geq 10^2$ - $10^3$ $(L_*/c)$). The thrust observed to be associated with the smaller scale ionized outflows is also incapable of driving the molecular gas ($(\dot{M}v)_{ion} \simeq (L_*/c)$, Persson et al 1984). The results may be explained if bipolar flows are hydromagnetic winds from molecular disks around protostars. These winds carry off disk rotational energy (observed as the mechanical energy of the outflows) and angular momentum (observed when rotation of the outflowing gas is found), which drives an accretion flow through it and onto the protostellar core ( Pudritz 1985, Pudritz and Norman 1983, 1986). Therefore star formation and bipolar outflows occur simultaneously when magnetized ,rotating disks are the source of activity.

The winds are centrifugally driven and initiated by the thermal pressure of the disk envelope. The envelope is heated by the Ly continuum and UV radiation which is released at a disk/core accretion shock wih an efficiency $\epsilon$. The Ly continuum ionizes an inner envelope out to a disk radius of $10^{15}$ cm which is the base of the VLA and optical emission line flows. The UV radiation warms a molecular envelope at larger disk radii and these outer reaches of the disk are the origin of the molecular outflow. The centrifugal drive accelerates gas to terminal speeds of $v_\infty \simeq v_{rot} \cdot (R_A/R_d)$ (eg. a disk rotating at 5 km $s^{-1}$ with the Alven surface $R_A$ at 10 disk radii, drives a 50 km $s^{-1}$ wind). Typical results are that the inner ionized outflow achieves mass loss rates $\dot{M}_{ion} \simeq 10^{-6}$ $M_\odot$ $yr^{-1}$ and $v_{ion} \simeq 250$ km $s^{-1}$ , while the outer molecular outflow may have $\dot{M}_{mol} \simeq 10^{-4}$ $M_\odot$ $yr^{-1}$ and $v_{mol} \simeq 50$ km $s^{-1}$.

The theory is applicable to both low and high mass star formation, the prediction being that low and high mass disks are the relevant sites. An example of lower mass star formation is in L1551. Here the mechanical energy of the outflow is $E_w \simeq 0.7 \times 10^{44}$ erg which is equated to the disk rotational energy. It follows that if the outer edge of the disk $R_d$ is the centrifugal support radius, then for L1551, $M_d = 2.2\, R_{16}^{\frac{1}{2}}\, M_\odot$ , $v_{rot} = 1.8\, R_{16}^{-\frac{1}{4}}$ km $s^{-1}$ and $(M_c/M_\odot)/(R_c/10^{12.5}\ \mathrm{cm}) = 1.4\ (0.1/\epsilon)\ R_{16}^{-\frac{1}{2}}$ where $R_{16} = (R_d/10^{16}\ \mathrm{cm})$, $M_c$ and $R_c$ are the core mass and radius. Therefore if such a rotating disk is resolved at a radius of $10^{15}$ ($10^{16}$ ) cm, the predicted disk characteristics are $v_{rot} = 3.1\ (1.8)$ km $s^{-1}$ , $M_d = 0.7\ (2.2)\ M_\odot$ , and $(M_c/M_\odot)/(R_c/10^{12.5}\ \mathrm{cm}) = 4.3(1.4)\ M_\odot$ assuming that $\epsilon = .1$.

A one parameter theory for the outflows and their associated disks can be prescribed by assuming a power law relation between the disk specific angular momentum and mass, $h \propto M_d^\alpha$, and using the relations given in Pudritz (1985) . Since the luminosity of the embedded infrared source is due to accretion through the disk onto the core, the luminosity $L_*$ can be used. The calculation may be done for any $\alpha$ , but an interesting choice is $\alpha = \frac{2}{3}$, a relation obeyed by massive pre main sequence rotating stars. The wind luminosity then scales as $L_w \propto L_*^{1.62}$, while the thrust for the molecular gas scales as $(\dot{M}v)_{mol} \propto L_*^{1.38}$. These scalings compare rather well with the correlations observed in the sample of bipolar outflows compiled by Bally and Lada (1983). The Table gives the results of a calculation based on a $\alpha = \frac{2}{3}$ disk specific angular momentum distribution where the normalization is chosen such that a 100 $M_\odot$ disk drives a wind with a mechanical energy of $10^{47}$ ergs. Since stars in this picture are accreted out of disks, this scaling shows that star formation in low, intermediate, and high mass disks ( 1, 10, and 100 $M_\odot$ ) is associated with characteristic wind energies of $10^{43}$, $10^{45}$, and $10^{47}$ ergs respecitively. It will be interesting to compare the frequency of outflows at various energies with an IMF when a complete sample becomes available.

| $M_d$ ($M_\odot$) | $E_w$ ($10^{43}$erg) | $B_d$ ($10^{-3}$ Gauss) | $v_{mol}$ (km s$^{-1}$ ) |
|---|---|---|---|
| 100 | $10^4$ | 10 | 50 |
| 10 | 220 | 4.6 | 27 |
| 3.5 | 7 | 3.4 | 21 |
| 1 | 4.6 | 2.2 | 15 |

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THOMPSON: Do your ionized regions match the $N_e{}^2V$ values indicated by the infrared lines which are much higher than the radio values? Also the ionized mass loss may vastly underestimate the total mass loss. The Ca triplet emission indicates large amounts of neutral gas entwined with the ionized gas as both have the same velocity structure.

PUDRITZ: The inner ionized envelope of the disk has, for the more massive disk model, a density of about $n_e \sim 4\times10^6$ cm$^{-3}$ (Pudritz 1985). The outer edges of this inner disk envelope lay at about $10^{15}$cm, so that the emission measure is of order $N_e{}^2V \sim 10^{59}$. This may be expected of sources with luminosities of $\sim 10^3$ $L_\odot$. Your point about neutral outflow is interesting. The theory presented here argues that neutral material is accelerated off the disk at larger radii from the protostar than completely ionized gas. Presumably there is a zone near the boundary between these which is relatively cool and mainly neutral. If there is a sharp boundary to the ionized gas, it would not be surprising that a neutral component, in which CaII emission occurs, has the same velocity structure. The centrifugal drive depends mainly on the magnetic flux, disk rotation frequency, and wind mass loss rate. As long as these vary more gradually with disk radius than the envelope's ionization state, one could still accommodate the observation which you describe.

ZINNECKER: In your model, at what stage of accretion is the bipolar outflow turned on and at what stage is it turned off? If, during the phase of outflow, only a small amount of mass is added to the stellar core, then the angular momentum problem for the star must be solved before the outflow phase, i.e. bipolar outflows will not solve the angular momentum problem in star formation. In other words: what is the disk-to-star mass ratio at the onset of the bipolar outflow?

PUDRITZ: The centrifugally driven wind is initiated when a small disk envelope can be heated. The geometry of the threading field is also important; gravitational contraction of the disk should have pulled in the molecular cloud field. The angular momentum problem is more difficult to solve in more massive systems because magnetic coupling is more difficult to maintain. I think therefore that whereas Alfvén wave braking, as discussed by Mouschovias, Mestel, and others, is important for lower mass disks, more massive systems ($M > 1\ M_{\odot}$) may resort to these massive, centrifugally driven winds. Finally, I believe that the total mass accreted onto a protostellar core out of the disk depends on how quickly the wind reaches the stage that $\dot{M}_w \cong \dot{M}_a$. I have made a "toy model" calculation of this recently (Pudritz, 1985, Astrophys. J. 293, 216).

SHU: Apart from the energy problem, there is a mass accumulation rate problem. If you have a wind loss rate $\dot{M}_W = 10^{-3} M_{\odot}\ y^{-1}$, then your disk accretion rate is $\dot{M}_a = 10^2\ \dot{M}_W = 10^{-1} M_{\odot}\ y^{-1}$, and you would accumulate a $10\ M_{\odot}$ star in $10^2$ y. This would seem to represent a very transient phenomenon.

PUDRITZ: The scenario you describe is based on the extreme case of star formation in a massive ($10^2\ M_{\odot}$) disk. In the case of Orion, one observes the most energetic of bipolar flows ($10^{47}$ergs). In this extreme case, the calculations in Pudritz (Astrophys. J. 293, 1985) give mass loss rates of *at most* $10^{-4}\ M_{\odot}\ yr^{-1}$from the surface of a $10^2\ M_{\odot}$ disk. In $10^4$ yr, something of order $50\ M_{\odot}$ might be accumulated if this rate were constant. I do think however, that in Orion it is exactly such a star which is forming. If, according to Snell, we are seeing enough bipolar outflows inside a 1 kpc circle, to account for the formation of all stars with $\gtrsim 1\ M_{\odot}$, then a few massive O stars must be amongst this group, I believe the Orion flow is precisely this. Note that the accretion rates, disk masses, outflow energies, etc. will be far less extreme for low mass star formation (as in L1551). Finally, I do agree with you that the accretion rate does evolve over the anticipated life-times of the outflows. I have attempted a simple time evolution model, and Pudritz and Norman (1986, Astrophys. J. 301). Suggest that the FU Orionis phenomenon might be the last spurts of accretion of material out of a depleted disk, onto the nearly completed young stellar object.

UCHIDA: Would you elaborate somewhat more about the magnetic field configuration in order to make clear the difference between our models?

PUDRITZ: A centrifugally driven wind has a toroidal field $b\phi$ which is somewhat weaker than the poloidal field near the disk: i.e. $(b\phi/b_p) \lesssim$

1. As the wind accelerates between the slow magnetosonic and Alfvén points the toroidal field grows somewhat due to inertia of the accelerating gas. Beyond the Alfvén surface, the toroidal field begins to dominate. Gas acceleration is more or less over and the growing toroidal field pinches and helps collimate the bipolar flow. Thus, far from the disk $(b_\phi/b_p) \gg 1$. In the models of Uchida and Shibata as I understand them, acceleration of gas occurs because a rapidly contracting and rotating disk wraps the threading field up to create a strong toroidal field near the disk. The presence of an outwardly directed $\nabla(B_\phi^2/8\pi)$ pressure force pushes out the gas. It would seem then that the field signature is strongly toroidal at the *disk surface*, becoming less so in the far field. This is probably observationally testable.

MOUSCHOVIAS: You made some very strong statements, one of which was that bipolar flows resolve the angular momentum problem during star formation. That, simply, is impossible. The angular momentum problem lies in the fact that, for wide binaries to form, at least two orders of magnitude of angular momentum must be lost by a contracting cloud (e.g. see 1977, Astrophys. J. 211, 147); for single stars to form, which is the case you are considering, you need to lose five orders of magnitude. To put it differently, contraction will stop because of centrifugal forces at much lower densities than the density of your disk. There is no alternative but to resolve the angular momentum problem before the protostellar disk stage is reached whatever "problem" is left at the disk stage, it is negligible by comparison.

PUDRITZ: I agree with your suggestion that significant magnetic braking by torsional Alfvén waves, must have occurred in the pre-disk stage in which clumps are contracting. While an H I "Spitzer cloud" may have a specific angular momentum of $10^{23} \sim 10^{24}$ cm$^2$ s$^{-1}$, none of the disks discovered so far has had such a high value. The point here however, is that for the disk around IRC2 in Orion, a 2-5 km s$^{-1}$ rotational speed is measured for a clump which is extended to a radius of order 2500 A.U. (Plambeck *et al.* 1984). A conservative estimate of the specific angular momentum in the outer reaches of this disk is then about $10^{21}$ - $10^{22}$ cm$^2$ s$^{-1}$. Evidently the clump (which may be rather massive; $\gtrsim 10\ M_\odot$) has been stripped of 99% of its original specific angular momentum, but still stores an interesting amount in its periphery. The mean disk density in the clumps of $10^2\ M_\odot$ may be $\sim 10^8$ cm$^{-3}$. Evidently, ambipolar diffusion of magnetic field is important at this value, and I have tried to estimate the coupling between field and disk (Pudritz 1985). As a final remark, I would guess that lower mass disks underwent far more braking while in their diffuse state; but again, I suspect that an interesting amount may still be left to act as flywheel for an energetic bipolar outflow.

MIRABEL: Could you comment on the magnetic field intensity and structure at distances of 0.1 to 0.5 pc form the disk?

PUDRITZ: The magnetic field at the midplane of a 100 (1) $M_\odot$ mass disk is of order $10^{-2}$ $(10^{-3})$ Gauss. A massive disk may be $10^{16}$ cm in size. Conservation of poloidal flux then, would give a field strength of order $10^{-4}$ $(10^{-5})$ Gauss at 0.1 pc. Notice however, that beyond the

Alfvén surface $R_A$, the toroidal field begins to dominate and it decreases less quickly, i.e. $b\phi \propto r^{-1}$.

## Hα AND [S II] DIRECT IMAGES OF HERBIG-HARO OBJECTS 1 AND 2 WITH THE MEPSICRON DETECTOR

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Using the Mepsicron detection system, we obtained images of the region around Herbig-Haro objects 1 and 2. These images were taken with interference filters centred on Hα, on the red continuum (6648 A) and on the [S II ] line at 6731 A.

We found two conical nebulosities connecting the central radio continuum source to HH1 and HH2. The emission lines (Hα and [S II]) are produced *in situ*, probably being excited by a shock wave created by the stellar wind emerging from the central source. Continuum emission is probably produced by reflected light from the same source. Some 10 arcsec to the NE of the central source we detected a small nebulosity with strong sulphur emission. Similarly, two emission knots were found ∿ 20 arcsec W of this source.

The sulphur to hydrogen ratio indicates that this nebulosity, as well as the two knots, are collisionally ionized. We did not detect optical emission from the central radio continuum source. This implies a limiting visual magnitude of 21.5 for the object.

## THE STRUCTURE OF THE HH39 REGION

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HH39 is the group of Herbig-Haro (HH) objects associated with the young semi-stellar object R Monocerotis (R Mon) and the variable reflection nebula NGC 2261. An R CCD frame and a B prime focus plate of the region show a filament connecting NGC 2261 with HH39, confirming the association between R Mon and the HH objects. This filament is probably composed of emission material. The southern knot in HH39 has brightened