Jets from Young Stars

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Abstract Most stars produce spectacular jets during their formation. There are thousands of young stars within 500 pc of the Sun and many power jets. Thus, protostellar jets may be the most common type of collimated astrophysical outflow. Shocks powered by outflows excite emission lines throughout the spectrum, exhibit a rich variety of structure, and motions with velocities ranging from less than 20 to over 500 $\mathrm{km\,s^{-1}}$. Due to their relative proximity, proper motions and structural changes can be observed in less than a year. I review the properties of classical Herbig-Haro objects, irradiated jets, and outflows emerging from the nearest massive star forming regions. Protostellar outflows are ideal laboratories for the exploration of the jet physics.

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1 Introduction

Protostellar jets and outflows produce the visual-wavelength shocks knows as Herbig-Haro (HH) objects [17]. HH objects are among the most beautiful astronomical objects in the sky and provide deep insights into jet physics in general. Because most forming and young stars produce bipolar jets and outflows, they are abundant with many examples located within a few hundred parsecs of the Sun. HH jets provide crucial insights into the launch, collimation, propagation, and the physical properties of jets in general.

Bipolar outflows and jets are powerful probes of various aspects of star formation. The detection of HH objects or other signatures of an outflow provide one of the easiest means by which to identify the presence of a young star. Over the past decades, many young stellar objects (YSOs) were first identified by the detection of their outflows. The structure, velocity field, and symmetries of outflows provide powerful diagnostics of protostellar accretion processes and dynamical interactions in multiple star systems and in clusters. The sizes of gaps between major shocks point to strong variations in the ejection velocity and mass-loss rates of the source YSOs. The giant, parsec-scale outflows provide constraints on the mass-loss histories of their source stars extending from 10^4 to over 10^5 years, a time-scale comparable to the formation time-scale of young stars. The spacing of major shocks indicate that major eruptions occur roughly every few thousand years. The close-connection between accretion and mass-loss implies that accretion onto YSOs is episodic.

The terminal shocks in outflows probe the interaction zone between protostellar ejecta and the ambient medium. Thus the most distant shocks from a source serve as mechanical probes of the interstellar medium with which they interact. The observed properties of the shocks provide information about the density and velocity structure, ionization state, and chemical composition of the medium.

Protostellar outflows have a profound impact on the star formation environment. In the absence of massive stars, their momentum and energy injection can be a major source of turbulence generation and cloud disruption. Thus, outflows in low- to intermediate-mass star forming regions may dominate the mechanism by which star formation self-regulates. In such environments, outflows may be the most important source of feedback.

Because of their proximity and large numbers, the time-evolution of protostellar outflows can be studied in a variety of ways. Thus, they provide powerful lessons that can be applied to the study of all classes of astrophysical collimated outflow.

2 Classical Herbig-Haro Objects

YSO accelerate winds and jets to velocities of 10s to over 500 $\mathrm{km\,s^{-1}}$, several times the escape-speed from the innermost regions of protostellar disks. Internal shocks form where faster ejecta overruns slower material. Low relative collision velocities (less than about 40 km s^{-1}) tend to excite the near-IR lines of H_2 if the medium is molecular and the near-IR lines of [FeII] and the visual-wavelength [OI], and [SII] lines if the medium consists of mostly weakly ionized atoms. Faster relative velocities (>60 km s^{-1}) can lead to the ionization of hydrogen. Charge exchange and collisional excitation form thin zones that radiate only in hydrogen recombination lines, the so-called "Balmer filaments". The layer of fully ionized hydrogen is followed by a recombination and cooling zone where both Balmer and forbidden lines are produced. This zone tends to have temperatures of order 10^4 K, set by the thermostating effects of the common, visual-wavelength forbidden lines. At most only one Hα photon can be produced by each recombining H atom because collisions do not have sufficient energy to excite the $n = 2, 3$, or higher energy levels of H. However, the 2 eV forbidden transitions of species such [SII] can be readily excited by collisions. As hydrogen recombines, the low electron density insures that trace ions have long lifetimes so that their forbidden lines can be collisionally excited over and over before they recombine. Thus, the intensity of the forbidden emission lines can become comparable to or greater than Hα. Shocks with speeds higher than about 150 km s^{-1} excite species such as [OIII]. Shocks with speeds lager than about 300 km s^{-1} can sometimes be detected in X-rays and non-thermal radio emission.

When launched from Class 0 or young Class I sources, primary flows tend to be molecular and are often traced by species such as H_2, CO, and SiO which typically exhibit radial velocities of 20 to 100 km s^{-1}. Outflows from Class 0 sources are very dense with n(H_2) in the range 10^4 to over 10^7 cm^{-3}, have large mass loss rates of order 10^{-6} to more than 10^{-5} $M_\odot$ yr^{-1}, and high mechanical luminosities. Weak maser emission in species such as H_2O are occasionally seen in the youngest outflows from low-mass stars. However, bright maser emission is generally associated only with high-mass protostars.

Somewhat more evolved Class I YSO tend to drive faster jets dominated by HI and low-ionization potential metals rendered visible by their forbidden line emission, have lower densities around 10^2 to over 10^4 cm^{-3}, and higher speeds in the range 100 to 400 km s^{-1}. More evolved Class II YSOs (classical T-Tauri stars) tend to have much fainter and lower mass-loss rate jets.

Primary jets and winds transfer momentum to and entrain their surroundings by means of low-velocity shocks propagating into the medium. These shocks can sometimes be seen in H_2 emission when the interaction is with the molecular cloud. Most high-velocity molecular emission observed at sub-mm, mm, and cm wavelengths is produced by gas entrained and accelerated by such secondary shocks. Species such as CO and other molecular transitions probe the mass and radial velocity of swept-up and entrained gas in an outflow, but only in the molecular cloud. When primary jets and winds blow out of their parent clouds, they no longer entrain molecules. Sometimes, the 21 cm line of HI can be used to trace the entrained atomic gas. The mm-wave transitions and HI are excited by collisions at the ambient gas temperature of the cloud and therefore do not require shocks to be observable. CO, other easy-to-excite molecular transitions, and HI when it can be discerned from Galactic emission, trace the total amount of momentum injected into the cloud and the amount of mass accelerated by an outflow over its lifetime.

Protostellar jets vary in their ejection velocities, mass-loss rates, orientations, and probably degree of collimation. Ejection velocity variations with amplitudes of tens of km s^{-1} on time-scales ranging from months to decades produce low-excitation shocks that render jets visible close to (within less than 0.1 pc) their sources. Larger but less frequent variations in ejection velocity, and presumably mass-loss rates, are responsible for the outer shocks and large gaps in between. Large eruptions associated with big velocity increases over-take older, slower ejecta to produce the giant, usually chaotic shock complexes located from 0.1 to many parsecs their driving YSOs. The giant HH 34 outflow complex in Orion provides a beautiful example [7]. Dozens of parsec-scale outflows, some of which have lengths exceeding 10 pc have been identified [16].

Internal shocks often splash sideways and contribute to the creation of relatively wide-angle outflow cavities filled with slower-moving material. Cavities may also be filled and formed by wide-angle winds launched at larger disk radii with lower velocities than the axial jets. Gas displaced and accelerated by these jets and winds may constitute the bulk of low-velocity material in bipolar molecular outflows which is traced by species such as CO.

Many outflows exhibit bends indicating C-shaped deflections or point symmetries. Such symmetries provide clues about the dynamical environment of the engine; S-and Z-shaped symmetries indicate that the outflow axis has changed over time, perhaps due to precession induced by a companion, or interactions with sibling stars in a cluster. C-shaped bends indicate motion of surrounding gas (side-winds), or the motion of the outflow source itself.

3 Irradiated Jets and Outflows

The discovery of irradiated jets embedded in HII regions and in UV-rich environments [2] permit the measurement of flow properties using the standard theory of photo-ionized plasmas which can provide a more robust method of density measurement than the analysis of the highly non-linear theory of shocks. External radiation renders visible much weaker jets and outflows than the flows seen in dark clouds where only shock processed gas can be seen at visual and near-IR wavelengths. Many irradiated jets have been discovered in the Orion Nebula and in NGC 1333 [2], in M43 [19], in the Carina Nebula [18] - see Figs. 1 and 2), and some other HII regions such as W5 (Stringfellow et al., this volume).

A significant subset of irradiated jets show extreme bends indicatting deflection by a side-wind, radiation pressure, or the rocket effect. The sub-arcsecond resolution of HST was required to identify dozens of irradiated jets in the core of the Orion Nebula [1, 3]. Some, such as HH 514 emerging from the proplyd HST 2, exhibit pronounced kinematic and intensity asymmetry. HH 508, emerging from one of the four companion stars to θ^1 Ori B, the northern member of the Trapezium, is a one-sided microjet which has the highest surface brightness of any known HH object in Hα because it is located within 10^3 AU of an OB star. Bally et al. [1] and Bally

Fig. 1 Irradiated jets in the Carina Nebula illuminated by the Trumpler 14 cluster. *A color version of this plot can be found in the electronic version of this book and in Appendix A (Fig. A.1)*

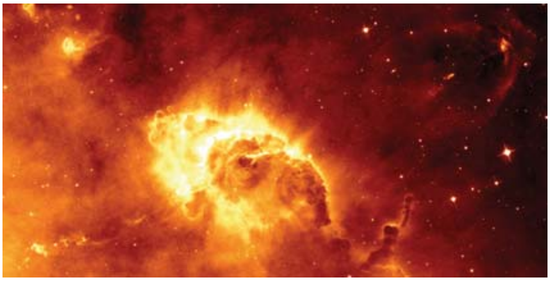

Fig. 2 The HH 666 irradiated jet emerging from dust pillars located southwest of η Car. The image was obtained with the ACS camera on the Hubble Space Telescope (see [18]). *A color version of this plot can be found in the electronic version of this book and in Appendix A (Fig. A.2)*

and Reipurth [2] noted that most low-mass stars located in the southwestern part of the Orion Nebula are surrounded by parabolic arcs of emission indicating deflection of circumstellar material away from the nebular core. These were dubbed 'LL Ori' objects after the prototype first noted by Gull and Sofia [10] who though that LL-Ori was an example of a wind-wind collision front. HH 505 contains both a jet and an LL Ori bow. Masciadri and Raga [12] modeled the HH 505 parabolic bow as a jet deflected by a side-wind. They were able to reproduce the Hα morphology of HH 505 and its source jet, showing that the bow is produced by weak secondary shocks formed where the side-wind interacts with jet material moving away from the jet axis after passing through the bow shock at the head of the jet.

The ACS images demonstrate that many LL Ori objects, including LL Ori itself, contain jets which are frequently asymmetric. Bally et al. [3] show that while most LL Ori-type bows and bent jets in the southwestern quadrant of the Orion Nebula may be deflected by a large-scale outflow of plasma from the nebular core, even in the absence of such a side-wind, radiation pressure acting on dust, and the asymmetric photo-ablation of a neutral jet beam can also deflect irradiated jets. As the neutral jet beam emerges from the circumstellar environment into the irradiated environment of the HII region, the photo-ionized skin of the jet expands away from the jet core. For most irradiated jets, the radiation field is highly anisotropic. Thus, the photo-ablation flow deflects the jet away from the illuminating star.

4 Outflows from Massive Stars

While most low-mass stars produce highly collimated jets and outflows during their formation, stars with masses above about $10^5\,M_\odot$ sometimes generate wide-angle and explosive flows.

The closest and best known example of a massive star forming complex is the BN/KL region in the OMC1 cloud core located immediately behind the Orion Nebula. A powerful and poorly collimated outflow emerges from a group of massive protostars embedded in BN/KL. Multi-epoch radio-frequency images show that the three brightest radio-emitting stars in OMC1, sources BN, I, and n, have proper motions (motions in the plane of the sky) of 26, 15, and $24\,\mathrm{km\,s^{-1}}$ away from a region less than 500 AU in diameter from which they were ejected about 500 years [8,9]. Apparently, a non-hierarchical multiple star system containing at least 4 massive members experienced a dynamical interaction resulting either in the formation of a tight binary or possibly a stellar merger whose (negative) gravitational binding energy ejected these stars from the OMC1 core. With estimated stellar masses of 10, 20, and $10\,M_\odot$ for BN, I, and n respectively, the kinetic energy of the stars is 2×10^{47} ergs, comparable to the kinetic energy in the CO outflow emerging from this region. This energy must be generated by the infall of two or more stars into a deeper gravitational potential well. Assuming that source I is a binary containing two $10\,M_\odot$ stars, its members must be separated by less than 11 AU, the orbital period must be shorter than 7 years, and the perihelion velocity of the stars must be at least $70\,\mathrm{km\,s^{-1}}$. The H_2 fingers and their optical counterparts (HH 201, HH 205 through 210) consist of hundreds of individual bow shocks that give the outflow the appearance of a wide-angle explosion. Proper motion measurements of the fingers indicate a dynamical age of between 500 to 1,000 years. This outflow is clearly *not* powered by a jet. Rather, it appears to have been created by an explosive event in the OMC1 cloud core.

My group has been developing a model in which at least 4 massive stars formed within the OMC1 cloud core. Assume that they started to accrete as low-mass protostars at random locations relatively far from each other within OMC1. As they orbited within the gravitational potential of the core they accreted gas by the Bondi-Hoyle process. Low-mass protostars and cores that happen to move toward the denser center will tend to accrete more material and experience orbital damping due to the combined effects of accretion and the gravitational drag of the wake that forms behind the stars (dynamic friction). Nick Moeckel has been modeling this process and finds that within a few hundred thousand years, the protostellar seeds grow into massive stars and sink to the center of the core where they form a non-hierarchical system of massive stars. Such systems are subject to three and four body encounters that eventually result in the formation of a compact binary and the dynamical ejection of the least massive members.

Prior to the dynamical decay, matter located within about 300 AU of the cluster, comparable to the interstellar separation, will either be accreted onto individual circumstellar disks that have outer radii smaller than about 1/2 to 1/3 times the typical interstellar separation, or be expelled to beyond 300 AU by gravitational torques. Taking the mean interstellar spacing before decay to be about 100 AU, the disk outer radii would be 30 AU where for a stellar mass of $10\,M_\odot$, the Kepler speed is about $17\,\mathrm{km\,s^{-1}}$. Since non-hierarchical multiples likely have chaotic orbits, disks may be truncated at somewhat smaller radii.

During the final penetrating encounter that led to the formation of an AU-scale binary whose gravitational potential energy expelled the stars from the region, the circumstellar disks of the stars that formed the binary would be destroyed. The interaction would eject their contents at roughly the Kepler velocity. If the binary consists of a pair of $10\,M_\odot$ stars separated by less than 6 AU as required by the energetics, the outer radius of any surviving disk around either star can be no greater than about 1 to 2 AU. Matter ejected from a 1 AU orbit around a $10\,M_\odot$ star would have a velocity of order $100\,\mathrm{km\,s^{-1}}$. Gravity will also accelerate the individual stars to about this speed if the periastron is a few AU. In a prograde (head-on) encounter between a star and the other star's disk, matter can be ejected with speeds of 200 to $400\,\mathrm{km\,s^{-1}}$.

It is proposed that the high velocities associated with the fastest ejecta in the BN/KL outflow were generated by the disruption of the inner-most portions of circumstellar disks around OMC1's most massive stars. The total mass of high-velocity ejecta is expected to be comparable to the initial masses of the circumstellar matter located between 1 to 30 AU; this could easily be comparable to the observed mass in the fast ejecta in Orion, about $0.1\,M_\odot$.

Orbital motion of the massive stars prior to the dynamical decay may have amplified magnetic fields within the OMC1 cloud core. If the shear-dynamo process if efficient, magnetic fields within a few hundred AU of the massive proto-cluster could reach equipartition with the gravitational potential. For the BNKL core, this implies mean magnetic field strengths of order 10 gauss in the inner few hundred AU of the cluster. The total amount of energy stored in such a magnetic field is around 10^{47} to 10^{48} ergs, comparable to the kinetic energies of the stars ejected by the dynamical decay and the OMC1 outflow.

After the stars were ejected about 500 years ago, the magnetic stress in the region would have exceeded the gravitational potential energy of gas and stars left behind. Thus, the magnetic fields would drive supersonic expansion of the magnetized medium at about the local Alfven speed which for conditions appropriate for OMC1 would have been about $20\,\mathrm{km\,s^{-1}}$, comparable to the observed velocity of the bulk of the mass in the OMC1 outflow traced by CO and other molecules.

In summary, it is proposed that orbital decay of a small group of accreting massive stars led to the formation of non-hierarchical cluster and the amplification of the ambient magnetic field to equipartition values. The dynamical decay of the stellar cluster ejected the stars from OMC1 (radio sources BN, I, and n). The disruption of the innermost circumstellar environments during the final close encounter that led to the formation of a compact binary (presumably source I) launched the fastest ejecta that produced the high-velocity H_2 and [Fe II] "fingers". The expansion of the magnetized medium accelerated the $10\,M_\odot$ associated with the lower velocity molecular outflow.

Located at a distance of 725 pc, the Cepheus A (Cep A) region is the second closest region of active high mass star formation. Observations also provide evidence

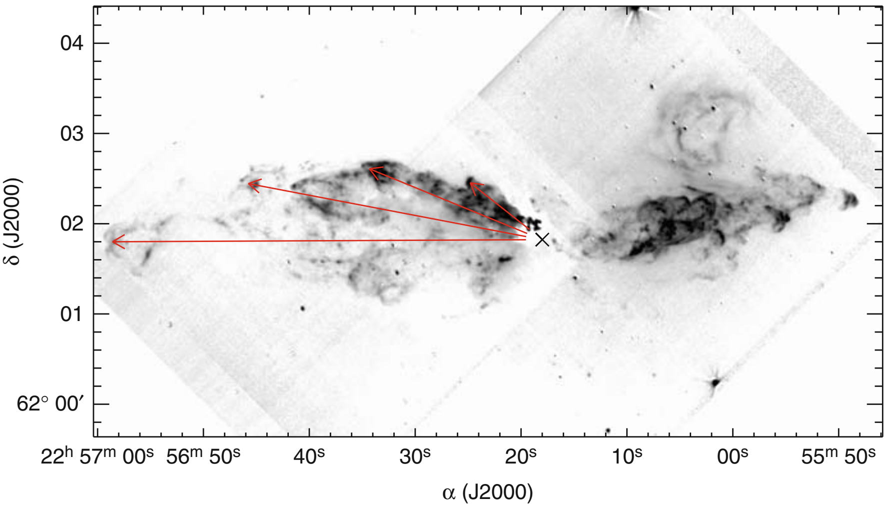

Fig. 3 The precessing beam of the HW#2 jet in Cepheus A as imaged in the 2.12 μm emission line of H_2. Taken from Cuningham, Moeckel, and Bally [4]

for dynamical interactions in that region. Recent near-IR H_2 observations have produced evidence that the $15\,M_\odot$ (B0.5; [15] and references therein) protstellar source HW2 produces a pulsed, precessing jet that has changed is orientation by about 45 degrees in roughly 10^4 years. Figure 3 shows that the eastern side of Cep A contains at least four chains of shock-excited H_2 emission that terminate in four distinct bow shocks. The bow shock orientations indicate that these flows emerge from the cluster of IR sources embedded within the Cep A cloud core, with the most luminous being HW2. HH 174, located 5' due east of HW2, is the most distant shock. Additional terminal bow shocks and shock trains are found closer to HW2, but displaced progressively towards the north with smaller position angles (PAs) with respect to HW2. The axes of these flows change in 10 degree increments from PA=90 to 45 degrees.

Observations with the VLA indicate that today, the thermal radio jet emerging from HW2 is oriented towards the northeast at PA $\sim$ 45 degrees and has motions of order $500\,km\,s^{-1}$ [6]. The orientations of the visual and near-IR reflection nebulosity is consistent with this latter outflow axis. An intriguing possibility is that since the ejection responsible for the HH 174 shock, the orientation of the HW2 outflow has changed by $45^c irc$ in discrete events during which outflow activity from HW2 increased dramatically. Thus, HW2 may drive a pulsed and precessing jet.

What could cause the orientation changes and periodic eruptions indicated by these observations? A likely possibility is forced precession of the accretion disk surrounding HW2 triggered by the motion of a binary companion in an eccentric orbit whose orbital-plane is NOT co-planar with the disk. Patel et al. [15] found direct evidence for a massive circumstellar disk surrounding HW2. Additionally, Martín-Pintado et al. [11] found evidence for a massive “hot core” displaced from HW2 by about 0.6”. The observed properties require that it is internally heated by a star with a projected separation of less than 500 AU from HW2. A third companion star may be responsible for the remarkable “water maser arc” found in Cep A [5].

Moeckel and Bally [14] have shown that, unlike low-mass ($\sim 1\,M_\odot$) stars, massive stars surrounded by massive disks have a relatively high probability of capturing a sibling cluster member into a highly eccentric elliptical orbit. We speculate that such capture occurred in Cep A HW2 about 10 to 20 thousand years ago. The resulting misalignment of the orbital plane and the HW2 disk can cause the disk to precess. Periastron passages of the captured companion may drive quasi-periodic episodes of accretion and mass-loss responsible for the pulsed, precessing jet evidenced by the observations. The effects of repeated passages of a non-coplanar companion in an eccentric orbit were investigated by Moeckel and Bally [13].

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