CONCLUDING REMARKS

CIRCUMSTELLAR MATTER, WITH PARTICULAR REFERENCE TO JETS AND MOLECULAR FLOWS

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ABSTRACT. Circumstellar matter exists in many forms, such as winds from early and from late type stars, in infra-red sources and OH and H_2O masers, in X-ray sources and jets, and molecular flows and Herbig-Haro objects. There is considerable diversity in the nature of the starlike bodies that underlie these phenomena. Here an attempt is made to trace the connection between some of the observations related to pre-main sequence stars and their surroundings, with emphasis on jets and molecular flows.

I. INTRODUCTION

The astrophysical significance of diffuse matter in space is now well-recognised. It has not always been so; the real change began with the development of radio-astronomical techniques, notably the use of the 21 cm line for the observation of atomic hydrogen in interstellar clouds. Since then many other parts of the spectrum have been opened up, and our understanding has improved with each new band of wavelengths. One only has to consider how the ultra-violet observations made with COPERNICUS entirely changed our views of interstellar physics, and its greatest contribution was the discovery of mass loss from early type stars as far as this Symposium is concerned. Developments in other parts of the spectrum have been equally worthwhile, and so has the application of new techniques; molecular spectroscopy at microwave frequencies has been used to map the structure of circumstellar regions, infra-red observations have probed deep into the dust clouds around newly formed stars, radio interferometers have revealed in great detail the very fine structure that exists in maser sources around both young and evolved stars, and X-ray satellites, notably the EINSTEIN Observatory, have detected significant emission from the vicinity of a wide variety of stars.

Our Organising Committee were very wise to decide that the time had come for a major meeting to review the whole subject of circumstellar matter. Their reward, a harvest of 175 talks and poster papers, testifies to the widespread interest and activity in this branch of astrophysics.

I. Appenzeller and C. Jordan (eds.), Circumstellar Matter, 571–580.

II. THE FORMATION OF MASSIVE STARS

To a large extent the proceedings of this meeting have continued the discussions that took place in Tokyo last November, at the highly successful IAU Symposium 115, on Star Forming Regions. It is now agreed that star formation takes place preferentially in giant molecular clouds, and that certainly in the case of the more luminous stars it occurs mainly near the potential troughs in the gravitational field caused by the spiral arms of the Galaxy. The stars themselves condense from diffuse gas following the collapse of a molecular cloud under its own gravitation. The process is only moderately efficient at best: it is estimated that typically only a few per cent of the mass of such a cloud is converted into stars and that the remainder stays diffuse or is returned to the diffuse state. Inevitably then the space around newly formed stars is full of circumstellar matter, which manifests itself in quite distinct ways depending on the mass and luminosity of the newly formed star. Its Kelvin-Helmholtz time t_{KH} is an important physical parameter, and so is the collapse time t_{coll} of the mother molecular cloud. Massive stars evolve rapidly towards the main sequence, so that their t_{KH} is less than t_{coll}. The star inside will reach its equilibrium state while there is still a copious inflow of material outside it. This accretion can continue only if the star is surrounded by a cocoon which converts its optical and ultraviolet emission into infra-red radiation. The direct stellar radiation cannot be allowed to reach the matter in the collapsing cloud at large: if it were to do so the repulsion of the gas-dust mixture by radiation pressure would far exceed the inward attraction by gravitation, and would soon halt the accretion. No bright star can form in the Galaxy unless it is enclosed in a circumstellar cocoon: the infra-red radiation which is created by the cocoon then pumps the OH and H_2O maser sources that often occur nearby. Eventually the star becomes luminous enough to drive away the cocoon, and the remaining circumstellar material associated with its creation, and can then be observed in the optical and the UV.

III. X-RAYS AND JETS FROM PROTOSTARS OF LOW MASS

Stars of smaller mass have a lower ratio of luminosity to mass, and also lower surface temperatures. Radiation repulsion of the accreting gas and dust around such stars is unimportant; on the other hand the Kelvin-Helmholtz time is now much longer, so that the mass falls onto the stellar surface much faster than the newly formed star can settle into its equilibrium state via radiative processes alone, and so the dynamics is significantly different. The problem with the massive stars was to discover how the accretion process can continue despite the intense repulsion by the radiation field. By contrast a less massive star cannot emit thermal radiation fast enough to rid itself of the gravitational energy that is released by the newly accreted material as it settles into its equilibrium configuration. It is reasonable to conjecture that the structure of the star remains unstable throughout this phase, and that the resulting mass motion leads to the acceleration of relativistic electrons.

The EINSTEIN observatory has in fact been used to find many pre-main sequence stars with a copious production of X-rays. Typically these sources emit photons with energies in the few keV range; the shock-heated gas that has just fallen on the star cannot radiate at such high frequencies. The X-rays must instead be produced by relativistic electrons via the synchrotron process, and so a significant magnetic field must exist in the star. Such a conclusion fits well with other ideas on the process of star formation: the presence of magnetic fields in and around protostars has long been conjectured, for without them it would be difficult for the infalling material to dispose of its angular momentum.

In all these examples the circumstellar material has come from outside the star. Even the relativistic electrons which emit the X-rays have gained their energy in regions where the ambient density is comparatively low, that is well above the photosphere.

Pre-main sequence stars of low mass are also sources of fast jets which have speeds of 200 to 300 km s^{-1} and are detectable by their Hα emission. Interesting consequences follow from the speculation that a physical connection exists between the jets and the X-ray emission.

Let the jet be collimated and the electrons be accelerated in a region with typical linear dimensions R. Let $\dot{M}_J$ be the mass-loss rate into the jet and V the flow speed. The jet luminosity is then $L \equiv \frac{1}{2}\dot{M}_J V^2$, and the momentum flux

$$\Pi_* = 2L/VR^2 \qquad (1)$$

can be used to scale the magnetic field strength B by the relation

$$B^2/8\pi \equiv \beta\Pi_* , \qquad (2)$$

with $\beta < 1$. Some of the mechanical energy of the jet will be tapped by its interaction with the surrounding medium. A relativistic electron can then gain energy from the mass motion at the rate

$$W_r \approx \frac{\gamma mc^3}{\ell}\left(\frac{V}{c}\right)^\alpha \quad ; \qquad (3)$$

in this formula ℓ is the typical distance between locations where successive reflections take place in the path of the relativistic electron, V is the typical velocity difference between the gas at these places, and γ is the Lorentz factor. In conventional Fermi acceleration reflections take place on eddies with uncorrelated motions, and α equals 2. If the acceleration takes place in a shock then every collision by a particle is head on, and the index α equals unity.

The X-ray photons from pre-main sequence stars typically have energy χ of about 5 keV, which corresponds to an angular frequency $\omega_X \sim 10^{19}$ s^{-1}. By the usual relations for synchrotron radiation

$$\omega_X \sim \gamma^2 \, e \, B/mc \qquad (4)$$

and the typical electron loses radiant energy at the rate

$$W_- \sim e^2\omega_X^2/\gamma^2 c \quad . \qquad (5)$$

Balancing the gains and losses, as given in equations (3) and (5), leads to the estimate

$$\ell \sim \frac{\gamma^3 mc^4}{\omega_x^2 e^2}\left(\frac{V}{c}\right)^{\alpha} \quad . \tag{6}$$

The orbital radius of a relativistic electron in the magnetic field is typically

$$r_o \sim \frac{\gamma mc^2}{eB} \equiv \frac{\gamma^3 c}{\omega_x} \tag{7}$$

and must be small in comparison with ℓ, so that

$$\omega_x < \frac{mc^3}{e^2}\left(\frac{V}{c}\right)^{\alpha} \quad . \tag{8}$$

The appropriate numerical values here are $mc^3/e^2 = 1.1 \times 10^{23}$ s^{-1}, $\omega_x \sim 10^{19}$ s^{-1}, and $V/c \sim 10^{-3}$, and so relation (8) can be satisfied if $\alpha = 1$, but not if $\alpha = 2$. The classical Fermi process cannot accelerate the electrons fast enough to make them emit the X-rays, but acceleration in shocks could do so. The thickness of the layer within which the acceleration takes place is typically of order ℓ, with $\alpha = 1$. The X-rays must also be generated in this layer, and it follows that the fraction of the available volume involved is of order ℓ/R, so that the total emitting volume is typically ℓR^2.

A constraint on this process is that the pressure due to the fast electrons should not exceed the magnetic pressure, or

$$\frac{1}{3}\gamma nmc^2 < \frac{B^2}{8\pi} = \frac{2\beta L}{VR^2}$$

so that

$$n < \frac{6\beta L}{VR^2 \gamma mc^2} \quad , \tag{9}$$

and the total number of radiating electrons is limited by

$$N = n\ell R^2 < \frac{6\beta L\, \ell}{\gamma V mc^2} \quad . \tag{10}$$

The total X-ray luminosity is given by

$$L_x = \frac{Ne^2\omega_x^{\ 2}}{\gamma^2 c}$$

and its ratio to the jet luminosity must satisfy

$$\frac{L_x}{L} < \frac{6\beta e^2 \omega_x{}^2 \ell}{\gamma^3 mc^3 V} \quad . \qquad (11)$$

The path length ℓ is given by relation (6) and on substitution it follows that

$$\frac{L_x}{L} < 6\beta \quad . \qquad (12)$$

From observation it turns out that L_X is typically 10^{30} erg s^{-1} and the jet luminosity L of order 10^{33} erg s^{-1}. The inequality (12) is easily satisfied unless β is very small. Physically this result implies that the hypothetical shocks need to cover only a small fraction of the cross-section of the jet and even so a sufficient number of electrons can be accelerated to yield the required energy output at X-ray frequencies.

A favourite theory has it that jets are formed when a stellar wind is collimated by a circumstellar accretion disk. Another, less popular, view is that the jet originates within the star itself, but the EINSTEIN observations seem to tally better with this mechanism. The X-ray luminosity is observed to fluctuate on a timescale of minutes or hours: suppose then that the jet really is collimated within the star. The flow speed must be larger just above the photosphere than at infinity, since the fluid still has to climb out of the stellar gravitational field. A jet moving at 500 km s^{-1} will advance 150 000 km in five minutes, a reasonable scale for the size of the emitting region on the star itself, but much too small for any feature that can realistically be associated with an accretion disk.

IV. A JET PUSHING OUT INTO CIRCUMSTELLAR SPACE

A jet is collimated on or close to a star and then has to force it way through the molecular gas in circumstellar space. It is natural to seek a connection between the presence of a jet and the large scale bipolar flows commonly observed near pre-main-sequence stars. Accordingly let the molecular gas be initially at rest, with a density distribution given by

$$\rho_o = \mu / r^2 \quad . \qquad (13)$$

As usual dust will be associated with the gas and so the mixture will absorb and scatter radiation. The typical value of the opacity is taken to be $\kappa_o = 200$ cm^{2}gm^{-1}, at visual wavelengths. The optical depth from far outside to within distance r_o of the star depends on the orientation of the line of sight, and is of order $\kappa_o \mu / r_o$. When μ is too large the optical depth is excessive; since fast jets are observed on typical length scales of 10^{17} cm it follows that μ should not be larger than 5×10^{14} gm cm^{-1}. The total mass of molecular hydrogen out to one parsec is thus limited to be less than some 10 $M_\odot$. Observed flow speeds in the molecular gas are typically of order 10 km s^{-1}, so that the energy content is of order 10^{46} erg (and proportionately less if the flow does not extend that far).

For comparison the mass loss rate into a jet is typically 10^{-7} $M_\odot$ per year, so that with a speed of 300 km s^{-1} the luminosity for a jet becomes 3×10^{33} erg s^{-1}.

During its early motion the jet is pictured as carving out a conical space with semi-vertical angle ε, say 0.1 radians, within which the gas flows freely. At the far end it passes through a shock, at distance r from the centre. The density in the jet immediately upstream of the shock is

$$\rho = \frac{\dot{M}_J}{\varepsilon^2 \pi r^2 V_J} \tag{14}$$

where V_J is jet speed, and the newly shocked gas has a cooling time

$$t_c = \frac{0.02 V_J^3}{q\rho} \quad , \tag{15}$$

where q is the usual cooling parameter. When r is sufficiently small the newly shocked gas stays hot very briefly and occupies only a thin layer just behind the shock. The condition is that

$$\frac{V_J}{4} t_c \ll \varepsilon r \quad ; \tag{16}$$

with numerical values inserted the right hand side becomes 7×10^{16}cm.

The layer of shocked gas itself drives another shock into the molecular gas at a speed w which is determined by balancing the momentum flow in the jet against the ram pressure in the gas outside; formally

$$\frac{\mu}{r^2} w^2 = \frac{\dot{M}_J V_J}{\pi \varepsilon^2 r^2}$$

or

$$w = \frac{1}{\varepsilon}\left(\frac{\dot{M}_J V_J}{\pi \mu}\right)^{\frac{1}{2}} \quad . \tag{17}$$

The speed of advance of the end of the jet is found to be 35 km s^{-1}, for representative numerical values, and with μ set equal to 5×10^{14} gm cm^{-1}. A distance of 7×10^{16} cm is reached after 2×10^{10} s, or 700 years. The energy carried by the jet is substantially converted into radiation just behind the shock, but is unlikely to be observed directly since the effect of circumstellar extinction is large at optical and UV wavelengths for a line of sight that comes so close to the star, and because this phase in the evolution of the jet lasts only a short time.

V. FOCUSSING THE JET BY EXTERNAL PRESSURE

The very early phase in the growth of the jet ends when the characteristic cooling time of the shocked gas becomes too long. A bubble of hot gas then develops, the jet enters it at radial distance r_o. The pressure $P(\equiv \Pi_o \eta)$ in the bubble scales in terms of the ram pressure

$$\Pi_o = \frac{\dot{M}_J V_J}{\pi \varpi_o^2} \qquad (18)$$

at distance r_o, and here $\varpi_o \equiv \varepsilon r_o$. The sudden exposure to external pressure drives shocks into the body of the jet, with interesting dynamical consequences, but here the first question is how long the newly shocked gas stays hot. The adiabatic parameter κ can once again be expressed in terms of the pressure P just behind the shock and the density

$$\rho = \frac{4\dot{M}_J}{\pi \varpi_o^2 V_J} \qquad (19)$$

there, and is given by

$$\kappa^{3/2} = \frac{\eta^{3/2}\pi}{32} \frac{V_J^4 \varpi_o^2}{\dot{M}_J} \quad . \qquad (20)$$

The shocked gas cools after a time

$$t_c = \frac{\kappa^{3/2}}{q} = \frac{\eta^{3/2}\pi}{32} \frac{V_J^4 \varpi_o^2}{q\dot{M}_J} \qquad (21)$$

The external pressure deflects the flow through an angle of order $\sqrt{\eta}$ and so focusses it towards a constriction at a distance of order $\varpi_o/(\sqrt{\eta} - \varepsilon)$ from the inlet. The gas there still retains its heat from the first shock if

$$\frac{\varpi_o}{V_J} < (\sqrt{\eta} - \varepsilon)\, t_c$$

or

$$\frac{(\sqrt{\eta} - \varepsilon)\eta^{3/2}\pi}{32} \frac{V_J^5 \varpi_o}{q\dot{M}_J} > 1 \quad . \qquad (22)$$

With the standard values assumed here the limits on η are as follows, for three different distances r_o

r_o (cm)	3×10^{16}	10^{17}	3×10^{17}
η_c	0.22	0.13	0.075
Δz_c (cm)	8×10^{16}	4×10^{16}	1.7×10^{17}
T_c (K)	2.7×10^5	1.6×10^5	9×10^4

In this table Δz_c denotes the distance between the inlet and the constriction, when $\eta = \eta_c$ and T_c denotes the post-shock temperature of the gas. If η exceeds η_c the gas is still hot when it reaches the constriction. Another shock then deflects the flow outward again. If $\eta_c > \eta > \varepsilon^2$ the shocked gas can cool before it reaches the axis. It will then shock a second time and will again cool off, so that a more compact jet reforms. It is tempting to identify these pockets of cooling gas with Herbig-Haro objects. If the flow remains steady then the resulting HH objects will be stationary, even though the gas is streaming through them at high speed. But observation shows that some HH objects have very large proper motions. They too can be fitted in if this description is altered slightly. The second shock occurs after the gas flow has converged on the axis. Such flows are generally unstable. It is to be expected that the gas is not evenly heated after passing through the second shock, so that some parts of it will cool better than others. A parcel of gas that is heated too well will then disperse again, and another that is not heated enough will cool efficiently, and as it is swept away down the axis it will be observed as an HH object with a high proper motion.

VI. JETS AND MOLECULAR FLOWS

As time goes on the jet creates an ever-growing bubble, and the kinetic energy that it carries is thermalised after shocking on a working surface at the far end. The expanding volume of hot gas drives a shock into the surrounding molecular gas, which picks up about a quarter of the energy supplied. Radiative heat loss becomes progressively less significant, and eventually three-quarters of the energy from the jet is retained in the hot gas. The temperature in the bubble is consequently given by

$$\frac{kT}{m} = \frac{1}{4} V_J^{\,2} \quad , \tag{23}$$

the adiabatic constant of the gas is

$$\kappa = \left(\frac{kT}{m}\right)^{5/3} P^{-2/3} = 0.10\, V_J^{\,10/3}\, P^{-2/3}$$

and the cooling time is

$$t_c = \frac{\kappa}{q}^{3/2} = \frac{0.031 V_J^5}{Pq} \quad . \qquad (24)$$

The pressure is defined in terms of the ram pressure in the jet at the point where it enters the bubble (see relation (18)) and thus

$$t_c = \frac{\pi}{32} \frac{\varepsilon^2}{\eta} \frac{V_J^4 \, r_o^2}{q \, \dot{M}_J} \quad . \qquad (25)$$

Later in the evolution t_c becomes large compared with the dynamical time t, and the mass of hot gas is

$$M_h = \dot{M}_J t \quad . \qquad (26)$$

The density of the hot gas is

$$\rho_h = \frac{P_h}{kT/\bar{m}} = \frac{4\eta}{\pi\varepsilon^2} \frac{\dot{M}_J}{r_o^2 V_J} \quad , \qquad (27)$$

and the bubble occupies a volume

$$V = \frac{\pi\varepsilon^2}{4\eta} r_o^2 V_J t \qquad (28)$$

whose radius is

$$r_h = 0.57 \left(\frac{\varepsilon^2}{\eta}\right)^{1/3} r_o^{2/3} V_J^{1/3} t^{1/3} \qquad (29)$$

if its shape is idealised to be spherical. The centre of the bubble is at distance $r_o + r_h$ from the star, but as time goes on the ratio of r_o to r_h becomes small so that r_o can be neglected. The density in the pre-existing molecular cloud is μ/r_h^2 at distance r_h, and the mass of molecular gas displaced by the bubble is

$$M_m = 2\pi\mu r_h = 3.60\mu \left(\frac{\varepsilon^2}{\eta}\right)^{1/3} r_o^{2/3} V_J^{1/3} t^{1/3} \quad . \qquad (30)$$

The molecular gas picks up a quarter of the energy carried by the jet in time t and so

$$\pi\mu r_h w^2 = \frac{1}{8} \dot{M}_J V_J^2 t \qquad (31)$$

or

$$w = 0.26 \frac{\dot{M}_J^{1/2} V_J^{5/6} t^{1/3}}{r_o^{1/3} \mu^{1/2}} \qquad (32)$$

A typical bubble has a radius of 1.5 x 10^{18} cm, say, and the associated molecular gas moves at 10 km s^{-1}; with typical numerical values inserted in relation (31) the age of such a structure turns out to be 100 000 years, and the parameter

$$\frac{\varepsilon^2}{\eta} = 0.0090 \frac{\dot{M}_J{}^3 V_J{}^3 r_h{}^6}{\mu^3 w^6 r_o{}^6} , \qquad (33)$$

roughly 9 at that time. The mass of swept-up molecular gas is 2.4 $M_\odot$, the pressure in the bubble and in the shell that surrounds it is 7.9 x 10^{-11} dyne cm^{-2}, and the hot gas has a characteristic cooling time of 800 000 years, much longer than the age of the bubble. The numerical values seem entirely reasonable, but the primitive description that has been given here does not do justice to the observations in one important respect. Flows of molecular gas are observed to be distinctly bipolar, with mean velocities that point outward from the star in each lobe. The present treatment fails to reproduce this effect because of the oversimplification that was introduced by the assumption that the bubbles are spherical. In reality a bubble will expand more easily into the direction away from the star where the ambient gas has a lower density. Bubble and shell both acquire an elongated shape, and the molecular gas reaches a higher speed outside than inside, so that the mean flow will be outwards. Even so the simple argument that has been used here does establish the physical connection existing between the jets and the surrounding molecular gas. Clearly this whole range of problems deserves a decent dynamical treatment. For some of us this is the next item on the agenda.

VII. CONCLUSIONS

A glance at the list of contents shows that the talks presented at this Symposium covered far more astrophysics than just the events associated with the pre-main-sequence stars. In particular apologies are due to the speakers who presented such beautiful results on stellar coronae and mass loss, on masers and infra-red studies, and on the chemistry of circumstellar matter. Given enough time and inspiration it might be possible to bring all the topics of this meeting together into one summary talk. Perhaps such a synthesis will be achieved by the concluding speaker at the next IAU Symposium on Circumstellar Matter. For the present it only remains for us to thank the Organising Committee for letting us take part in such a feast of talks containing so many new and fascinating results.