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HIGH-VELOCITY OUTFLOW SOURCES IN MOLECULAR CLOUDS: THE CASE FOR LOW-MASS STARS

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ABSTRACT

Using calculations of the evolution of single explosions and time-extended outflows in molecular clouds, the energy and time required to produce the high-velocity molecular outflow observed in Orion are derived for spherical expansion models. We find the energy efficiency of extended outflows is somewhat greater than that of single explosions in producing the observed velocity, radius, and mass of the outflow, but the efficiencies differ by less than a factor of 2. From the number of sources of high-velocity outflow, the present age of each outflow, and estimates of incompleteness of the detections, we estimate a rate of outflow occurrence more than 3 times greater than the formation of stars more massive than 4 $M_\odot$. We argue that low-mass stars are likely to produce the bulk of the outflowing regions in molecular clouds.

Subject headings: interstellar: molecules — stars: winds

I. INTRODUCTION

Molecular clouds contain at least 50% of the mass of the interstellar medium and are responsible for the formation of essentially all massive stars ($M > 5\ M_\odot$). There is little direct observational evidence on the formation site for low-mass stars (of order 0.2–2 $M_\odot$), but it is quite likely that these stars are also produced mainly in molecular clouds. Although low-mass stars contribute little to the total optical luminosity, they have a higher formation rate.

Most of the material within a molecular cloud is at low velocities with respect to the center-of-mass velocity, with typical velocity dispersions of around 2 km s^{-1}. Many clouds are now known to contain some medium- to high-velocity material as well, with 20 km s^{-1} representative of this material, but there is also some material with velocities of order 100 km s^{-1} confined to a small volume. The best studied example of such a cloud is the Orion molecular cloud OMC-1 (Zuckerman, Kuiper, and Rodriguez Kuiper 1976, Kwan and Scoville 1976). The present paper is concerned with models for the high-velocity material, $v \sim 100$ km s^{-1} relative to the cloud center of mass.

Two classes of models have been proposed for Orion. In one class, the high-velocity material is swept-up gas at the outer edge of some expanding bubble or blast wave (e.g., Kwan 1977); in the other class, the high speed is reached by only a small fraction of the material and in a gradual manner (e.g., Harwit and Schmid-Burgk 1983). In the second class of models, the maximum temperature reached by any material is lower than that in the first class, and a smaller fraction of the total energy input appears at the highest speeds. There has been considerable theoretical effort aimed at describing the physics of the outermost, shocked gas, but there has been much less discussion of the overall evolution of the expanding gas and its source of energy.

In this paper, we examine how the evolution of the cloud depends on the source of the outflow. We argue (§ II) that the first class of models is most important for Orion, but there are a number of variants depending on whether energy is released in a single burst (e.g., supernova explosion) or over an extended period (continuous stellar wind or a series of smaller explosions or a series of magnetic energy releases), and depending also on the outflow velocity. The basic theory for these variants is available at least for uniform-density clouds (Weaver, McCray, and Castor 1977; Shull 1980*a*, *b*; Wheeler, Mazurek, and Sivaramakrishnan 1980). In § II and § III, we use these published calculations to derive and compare parameters for model variants, each adjusted to the same observational parameters which characterize the Orion high-velocity molecular material. It is useful to note that these calculations do not depend specifically on the outflow mechanism, for example, whether winds or explosions are driven by radiation pressure or by some other means. Density fluctuations, especially small, massive clumps embedded in a lower density medium, may affect the nature of the flow, and these are discussed in § IV. We comment on the qualitative effects of repeated bursts in § V, and in § VI we discuss the

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statistical arguments which indicate that the high-velocity flows occur frequently with relatively little energy per event. Such flows could be produced if low-mass stars undergo a short-lived, efficient phase of rapid mass loss during their pre–main-sequence evolution, and this possibility is discussed in § VII.

II. OBSERVATIONAL PARAMETERS AND COMMENTS ON THE CLASSES OF MODELS

The velocity and spatial structure of the medium- and high-velocity CO emission in the Orion molecular cloud OMC-1, commonly referred to as the "plateau feature," has been described by various authors including Zuckerman, Kuiper, and Rodriguez Kuiper (1976); Kwan and Scoville (1976); Kuiper, Rodriguez Kuiper, and Zuckerman (1978); Phillips *et al.* (1977); Solomon, Huguenin, and Scoville (1981); Knapp *et al.* (1982); Nadeau, Geballe, and Neugebauer (1982); and Scoville *et al.* (1982). The velocity profile of the $J=1{-}0$ line is very symmetric about the main velocity of the cloud, $v_{\rm lsr}=-9$ km s^{-1}. The emission extends at least to $|v|=100$ km s^{-1}. We assume the region is spherically symmetric and adopt a maximum velocity $v_{\rm shell}=100$ km s^{-1}; although there may be emission at higher velocities, it is assumed this emission does not account for a significant fraction of either the mass or kinetic energy in the flow. The high-velocity emission is confined to a projected radius of order 45″, corresponding to 0.1 pc at an assumed distance of 460 pc (Genzel *et al.* 1981). The radius is not well defined (for example, gas extends at least 60″ north of the infrared cluster, as seen in Fig. 1 of Beckwith *et al.* 1978), but the bulk of the high-velocity H_2 and CO emission is contained within this circle, and we purposely choose this radius to be large to find an upper limit for the age used in § VI. The velocity profile has a change of slope at $v=20$ km s^{-1}, and the antenna temperature per unit velocity interval dT_A/dv is approximately equal to $7500\,v^{-2.6}$ K/km s^{-1} for v between 20 and 100 km s^{-1} (Kuiper, Rodriguez Kuiper, and Zuckerman 1978).

The mass and kinetic energy in the outflow can be derived from the line profile as follows: Let $F(v)\,dv$ represent the total mass between velocity v and $v+dv$; then $F(v)=g(v)\,dT_A/dv$, where the conversion factor $g(v)$ from antenna temperature to mass is a function of the excitation temperature $T_{\rm ex}(v)$ and the volume density n. We assume optically thin emission. For the range of parameters of interest here, $g(v)$ increases almost linearly with $T_{\rm ex}(v)$ but is almost independent of n, so the degree of clumping is not very important; Zuckerman, Kuiper, and Rodriguez Kuiper (1976) found $g(v)=5.2\ M_\odot T_{\rm ex}(v)$. If we replace $g(v)$ by a constant g, the mass M and kinetic energy K between velocities v_1 and v_2 is of the form

$$\begin{aligned} M&=(g/1.6)\left(v_1^{-1.6}-v_2^{-1.6}\right),\\ K&=(g/0.4)\left(v_2^{0.4}-v_1^{0.4}\right), \end{aligned} \tag{1}$$

so that most of the mass is contained in the material near the lower limit v_1, but the kinetic energy is dominated by material near the upper limit v_2. The dependence $v_2^{0.4}$ is rather weak, but it is theoretically likely that the gas kinetic temperature increases with increasing bulk velocity v, and since $g(v)$ is approximately proportional to $T_{\rm ex}$, the kinetic energy will be dominated even more by the highest velocity material. We shall be most interested in the highest velocity material near $v_2=100$ km s^{-1}, which is certainly optically thin. (The lower velocity material has higher density and may be optically thick.) Models of the outflow which employ a spherically expanding bubble or blast wave have most of the bulk kinetic energy in material with speeds approaching the maximum velocity v_s, and we therefore favor this class. If the expansion occurs in uniform-density gas, these models also assign most of the mass to high-speed material, contrary to the observations, since M in equation (1) is dominated by material near v_1, even if the temperature dependence of g were taken into account in a plausible way.

Any realistic model treating the emission at all velocities will have to consider inhomogeneities in the initial density n_0 and other complications; we comment qualitatively on some such refinements in § IV. As mentioned above, most of the emission comes from material at intermediate velocities (well below v_2) and higher densities; Draine and Roberge (1982) and Chernoff, Hollenbach, and McKee (1982) argue that magnetic fields are important for this material and that H_2 line intensity ratios require a rather well-defined shock speed near 38 km s^{-1}. The simple spherical models described below refer only to the higher velocity material, which carries most of the kinetic energy. Magnetic fields are less important for the high-velocity gas, and we shall ignore them.

III. SIMPLE SPHERICAL MODELS

To provide a basis for the comparison of the spherical models, we have chosen values for the radius R, the maximum velocity v, and the mass M of the outflowing gas in Orion. The radius and maximum velocity are approximately 0.1 pc and 100 km s^{-1}, as discussed above, and the total mass is 5 $M_\odot$, based on CO measurements (Zuckerman, Kuiper, and Rodriguez Kuiper 1976; Knapp *et al.* 1982). If the mass comes mostly from material swept up from the undisturbed cloud, then the average cloud density prior to the expansion was 3×10^4 cm^{-3}. We will compare the total energy input and expansion time for two spherical expansion models which are required to produce the observed radius, velocity, and mass of the outflow.

The first model is a single explosion of total energy E_0 into a cloud of uniform density n_0. This model is discussed by Shull (1980*a*) and Wheeler, Mazurek, and Sivaramakrishnan (1980) specifically for the high densities considered here. The initial adiabatic (Sedov) phase is short and of little interest, and the expansion quickly forms a cold, dense shell which moves outward just inside a shock front of radius R_s and velocity v_s. The velocity and radius of the shell are related to the expansion time by

$$v_s = (4.2\times10^{-6})(E_0/n_0)^{3/14}t^{-5/7}, \tag{2}$$

$$R_s = Av_st. \tag{3}$$

Here v_s, E_0, n_0, and t are in km s^{-1}, ergs, cm^{-3}, and years, respectively. The quantity A is a constant which varies from model to model, but is always of order unity (Shull 1980*a*). Fitting the adopted values of R, v, and n_0 with this model ($A = 3.5$) requires an age of $t = 290$ yr and an initial energy of $E_0 = 4\times10^{48}$ ergs. The kinetic energy in the shell is now 5×10^{47} ergs in this model, yielding an efficiency of 12%. The explosion model is the least efficient way of producing kinetic energy in a shell largely because radiative losses set in at an early stage during the expansion (at large shock speed) and continue. The actual kinetic energy is not confined to a shell, but the present calculation will mainly be useful to compare different models. We discuss modifications in the next section.

The second model considered here is outflow driven by a high-velocity wind (we will use the term wind to mean any continuous mechanical outflow) such as seen from many early-type main-sequence stars (Conti 1978). Castor, McCray, and Weaver (1975), Weaver, McCray, and Castor (1977), and Shull (1980*b*) discuss the evolution of this type of model. There is once again a short period of adiabatic expansion after which most of the lifetime of the expanding gas is spent in a snowplow phase which begins when swept-up gas collapses into a thin shell and is driven outward by pressure from a very hot gas interior to the shell. If the mechanical power of the wind or outflow L_m is constant with time, the velocity and radius of the shell are given by

$$v_s = 2.5\times10^{-4}\,(L_m/n_0)^{1/5}t^{-2/5} \tag{4}$$

and equation (3) with $A = 5/3$. For this kind of model, the radius and velocity of the gas in Orion are fitted by $L_m = 1\times10^{38}$ ergs s^{-1} at an age $t = 600$ yr. The total energy input from the wind is 2×10^{48} ergs after 600 yr, about 50% of that required by an explosion model to produce the same observed parameters. The high-velocity wind is somewhat more efficient in this case owing to lower radiative losses, but the total energy required is still more than the observed kinetic energy.

If the wind velocity is relatively low, there will be no true adiabatic expansion, and the evolution is governed mainly by momentum conservation with the wind momentum impinging directly onto the shell of swept-up cloud matter. We estimate that the upper limit to the outflow velocity for this case is 500 km s^{-1}, the velocity at which the time for the wind to sweep up its own mass is of the same order as the radiative cooling time, assuming line cooling in the shell with the rate given by Wheeler, Mazurek, and Sivaramakrishnan (1980). When the outflow velocity is slightly smaller than 500 km s^{-1}, the velocity of the shell is given by

$$v_s = 3.7\times10^{-5}(L_m/n_0v_0)^{1/4}t^{-1/2}, \tag{5}$$

and the radius is given by equation (3) (Steigman, Strittmatter, and Williams 1975). In equation (5), v_0 is the outflow velocity in km s^{-1}. The mechanical luminosity and age to fit the radius and velocity in Orion are 10^{38} ergs s^{-1} and 500 yr for an outflow velocity of 300 km s^{-1}. The total mechanical energy expended is 2×10^{48} ergs, and the efficiency for the low-velocity wind is similar to that for the high-velocity wind. The efficiencies calculated using equations (4) and (5) do not change smoothly from $v > 500$ km s^{-1} to $v < 500$ km s^{-1} because of the approximations used to obtain the different similarity solutions and uncertain boundary conditions. The efficiencies are nearly correct, however, and have the correct behaviors in the limit of very high and very low velocities.

The calculation of the evolution of the region is rather complicated for a very low-velocity outflow ($v_0 \sim 200$ km s^{-1}, say), but a very low-velocity outflow should be even more efficient at producing bulk kinetic energy in the gas than either the high-velocity wind or the explosion model. In the limit of outflow velocity equal to 100 km s^{-1}, there is no loss of energy, and the line profiles will resemble those for a uniform-density spherical outflow (e.g., Morris 1975). For a wind speed greater than 100 km s^{-1}, the region will consist of a shell of matter at v_s with an interior region of uniform outflow containing a significant fraction of the total mass and momentum. The efficiency will still be even higher than for the high-velocity wind by approximately the ratio of the wind velocities.

The important qualitative result of these calculations is the ratio of efficiencies. The ratio of observed kinetic energy to the required energy input in each of these models is of order the ratio of the observed velocity to the velocity at the end of the period of adiabatic expansion (in the case of the low-velocity wind, it is just the ratio of observed velocity to wind velocity). This conclusion will not be altered strongly either by the presence of inhomogeneities in the density or by the geometry of the flow. For the bipolar flows seen in many high-velocity regions, the conclusions will hold as long as the flow is collimated relatively close to the source, and the relative efficiencies should be approximately correct for the more complex geometries.

We have quoted model results from published calculations which were originally intended for steadily flowing, radiatively driven stellar winds, but the features we require are much more general: For instance, a series of sudden explosions would give similar results as long as there were enough of them (see § V). Further, the physical mechanism which first imparts momentum to the ambient medium does not matter; in particular, we shall argue against radiatively driven momentum transfer in § VII. For example, a series of events which first converts magnetic energy into kinetic energy of ambient material at some speed v_0 gives similar results to a stellar wind of wind speed v_0, as long as v_0 is larger than the presently observed CO velocities. We disregard here models where one is presently witnessing the first interaction of a stellar wind or magnetic disturbance with ambient material (see, however, Draine 1982).

IV. DENSITY FLUCTUATIONS

The ambient cloud medium through which a blast wave or stellar wind bubble propagates is likely to have appreciable fluctuations in preshock density n_0. These fluctuations lead to variations in shell speed v_s, but the details depend strongly on the geometry of the fluctuations. The simplest case consists of slow, smooth density variations which can be approximated by considering n_0 constant along any one radial direction θ, but with n_0 varying strongly with θ. The radius R_s and velocity v_s will then both vary with direction θ. If the density variation is very simple, such as in an azimuthally symmetric geometry with the highest densities in a plane near the source, the outflow may become collimated or bipolar, as is observed in several high-velocity sources. While it is more difficult to estimate the kinetic energy, momentum, and mass in this geometry, the overall efficiencies of the different models should be similar to the spherically symmetric case, since equations (2) and (4) depend weakly on the density.

If the density varies rapidly with direction, or if there is a substantial amount of matter in dense clumps which are small, the wind will expand primarily through the gaps between clumps in the "background" cloud material. The values of n_0, v_s, and R_s used in § II will then refer to this background material. The intermediate velocity emission (20 km s^{-1}, for example) presumably comes from secondary shocks propagating into the individual clumps. In this model, there is no close correlation between shock speed and distance from the center of the outflow, but the average radius is smaller for the intermediate velocity material, since clumps anywhere inside R_s can be shocked. The clumps absorb a certain fraction of the primary energy, but for the lower density "background" material, the expansion efficiency should not be decreased greatly unless the clumps occupy a large fractional volume in the cloud.

Chevalier and Theys (1975) have shown that, in principle, one can even have a reversal in the velocity-size correlation, in that a clump could move ahead of R_s. In practice, this case seems less likely than the situation described above. Accurate observations of the velocity-size relation would be very useful for distinguishing between these cases.

V. SUCCESSIVE BURSTS

The total energy and present age required to fit the Orion observations are not very different for a single explosion and for a steady high-velocity wind. A sporadic outflow over a total time period t with a total energy output E_0 has essentially the same consequences as a steady outflow with energy production rate E_0/t. However, an energy output E_0 over the last t years is much less efficient if there have already been similar outbursts over a much longer previous period. Mathematically, this can be seen from the scaling laws (see, e.g., Shull 1980*b*); physically, it stems from the fact that early outflows sweep out matter, making the effect of the subsequent outflows much less.

As noted below, the birthrate of high-velocity CO sources is large, and it is of interest to determine how often a single star could give rise to a high-velocity outflow if each burst is to be equally efficient. Suppose the burst phase $t+$ is much shorter than the duration of the quiet phase $t-$. If the time of quiescence $t-$ is long enough, the shell has time to dissipate, and once the initial conditions have been reestablished, the subsequent burst has the same efficiency as the previous one. The shell will stop expanding and begin to dissolve when (i) the velocity v_s reaches the sound speed or the turbulent speed of the matter in front of it, or (ii) self-gravity becomes important. For a turbulent speed of about 2 km s^{-1} and the parameters we have derived for Orion, these two times are comparable and are of order 2×10^5 yr, which is therefore the minimum interval $t-$ between successive bursts necessary to obtain the same efficiency for any of the outbursts. For the sources discussed in the next section, with similar energies to Orion but lower densities and larger ages, $t-$ would have to be quite long, of order 10^6 yr.

VI. OTHER BROAD-LINE SOURCES

Quite a few regions of star formation are now known to exhibit one or more of the characteristics of the Orion high-velocity outflow (Frerking and Langer 1982; Bally and Lada 1983, and references therein; Fischer 1981; Lichten 1982). Table 1 lists sources chosen from these four references to represent the high-velocity outflow in different regions along with our analysis of OMC-1. We took R and v from the literature using the largest observed velocities. We increased the observed R by a factor of 1.414 to correct for projection effects and to make t as large as possible so as to obtain lower limits to the birthrate discussed below. The present age and mechanical outflow luminosity L_m have been estimated

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TABLE 1

HIGH-VELOCITY SOURCES WITHIN 1 KPC

Object	t (10^4 yr)	L_m ($L_\odot$)	E_m (ergs)	D (kpc)	Ref.
B335	10	0.003	3×10^{43}	0.4	1
L1527	7	0.005	4×10^{43}	0.16	1
L723	2	0.1	3×10^{44}	0.16	1
L1455	2	0.3	6×10^{44}	0.16	1
OMC-2...........	0.6	0.5	4×10^{44}	0.46	2
L1529	0.5	1	6×10^{44}	0.14	3
L1551	3	0.08	3×10^{44}	0.12	4
Mon R2	7	80	6×10^{47}	0.8	4
S140	2	260	6×10^{47}	1.0	4
OMC-1...........	0.06	26000	2×10^{48}	0.46	4
HH 24–26	1	50	6×10^{46}	0.5	4
HH 7–11	1	80	9×10^{46}	0.5	4
Cep A	0.7	200	1.5×10^{47}	0.7	4
AFGL 490	0.8	500	5×10^{47}	0.9	4
NGC 2071	0.8	1000	1×10^{48}	0.5	4

REFERENCES.—(1) Frerking and Langer 1982. (2) Fischer 1981. (3) Lichten 1982. (4) Bally and Lada 1983.

for each source assuming the expansion is caused by an intermediate outflow velocity greater than 500 km s^{-1} with the constant $A = 5/3$. While this assumption is somewhat arbitrary, the total energy required to cause the expansion does not depend very strongly on the details of the expansion; therefore, these energies should be representative of the actual situation. As discussed below, the escape velocity of even the lowest mass stars is of order 500 km s^{-1}.

These sources represent a broad range of mechanical power L_m and various stages of evolution. It is interesting to note that most of these regions are older than 10^4 yr, and the outflow in Orion is the youngest. It is also useful to note that while at least one of these sources is comparable in energy to the Orion source, none is more energetic than 10^{48} ergs, in other words, much less than a typical supernova. On the other hand, many have energies greater than a typical nova or planetary nebula, with mass loss rates (m_m/t) larger than observed in main-sequence stars. The regions L1551 and L1529 in Taurus are particularly interesting in that the luminosities of the stars in the center of the outflows are less than 50 $L_\odot$ (Fridlund *et al.* 1980) and 2 $L_\odot$ (Van Duinen *et al.* 1982), respectively, so a luminous star is evidently not required for strong outflow.

We wish to estimate the rate of occurrence of outflows and to compare it (in § VII) with the birthrate function of stars of various masses. We consider events in a column based on a disk of radius 1 kpc in the galactic plane (centered on our location); since the vertical scale height of molecular clouds is small, this is equivalent to all CO sources within 1 kpc. Let $r_{\rm of}$ be the rate per 10^4 yr of onset of the outflows discussed in this paper within 1 kpc. The simplest and crudest estimate of $r_{\rm of}$ would be t_y^{-1}, where t_y is the age (in 10^4 yr) of the youngest outflow source in our volume. Taking $t_y = 0.06$ for OMC-1 gives $r_{\rm of} = 17$, but this is, of course, a very crude estimate. If all N sources between ages t_y and t_o in our volume were known, we could get a better estimate of $r_{\rm of}$ by noting that

$$\sum_{i=1}^{N} t_i^{-1} \sim r_{\rm of}\int_{t_y}^{t_o} t^{-1}\,dt = r_{\rm of}\ln\left(t_0/t_y\right), \qquad (6)$$

where t_i is the age of the ith source. This approximation is useful because we can perform the sum and the integral for known sources, and the uncertainty in $r_{\rm of}$ in the range of ages enters only in the logarithm.

In reality, only a fraction of all existing sources are likely to have been observed so far. Let W_i be the ratio of all sources of a given type (within our volume and with $t_y < t < t_o$) to those already observed. Pretend at first that all nearby sources of a given type have already been observed, but that we miss more and more as the distance D_i increases toward 1 kpc, because the area to be sampled for completeness increases as D_i^2. Let $\langle D_i^2 \rangle$ be the mean square distance (in units of 1 kpc^2) of the observed sources in a group; since 0.5 is the mean square distance of all sources in the group, we then use

$$\langle W_i \rangle = 0.5/\langle D_i^2 \rangle \qquad (7)$$

as an estimate for the mean weight factor W_i. We provisionally adopt

$$r_{\rm of} = \left(\sum t_i^{-1}\right)\langle W_i \rangle/\ln\left(t_y/t_o\right). \qquad (8)$$

For the sources in Table 1 we find for $\langle W_i \rangle$ approximately 1.7. The sum of the inverse ages, $\sum_i t_i^{-1}$, for all the sources is 29, and the ratio t_o/t_y is 170. We then get from equation (8) the estimate $r_{\rm of} \sim 10$ (kpc^{-2} per 10^4 yr). If even for the nearby sources the total number is larger than the presently observed number by some factor W_0, then our estimate for $r_{\rm of}$ has to be multiplied by W_0. It is interesting to note that the estimate of $r_{\rm of}$ obtained only from Orion is not very different from the $r_{\rm of}$ obtained from a more complicated analysis, so Orion may well be "typical" as an outflow source but simply younger than any of the other observed sources.

Our estimate for $r_{\rm of}$ is somewhat larger than that given by other authors, since we include a factor to correct for incompleteness. For comparison, Lada and Harvey (1981) give $r_{\rm of} > 1.3$; Solomon, Huguenin, and Scoville (1981) give $r_{\rm of} = 1.4$; and Frerking and Langer (1982) give $r_{\rm of}$ between 4 and 20.

VII. THE CASE FOR LOW-MASS PRE–MAIN-SEQUENCE STARS

In comparing different models for the source of the high-velocity emission, one has to distinguish four requirements: the rate of momentum transfer, the rate of occurrences by number, the energy per occurrence, and the time duration. As already discussed by many authors, radiation pressure is a very inefficient means for transferring momentum, and models using radiation pressure directly can be eliminated in favor of those using bulk motion originating from a star. For models using bulk motions induced by individual stars, the most stringent requirement is the high rate by number, not the energy: Massive stars could produce orders of magnitude more energy than required for one occurrence, but we noted in § V that if massive stars were to produce all outflows through repeated bursts, the intervals between bursts would have to be of order 10^6 yr, comparable to the main-sequence lifetime of a very massive star. Thus, each star can produce a few (or more probably only one) high-velocity outflows in its lifetime, and it is of interest to compare our estimate r_{of} for the birthrate of CO-emitting outflows with $r(M_e)$, the birthrate of stars with mass $M > M_e$. Miller and Scalo (1979) have given a thorough review of the stellar initial mass function and related topics: Although the time dependence and spatial variation of the stellar birthrates are still controversial, the present rate of star formation (per 10^4 yr) in our vicinity (column of radius 1 kpc) is fairly well known. In particular, Miller and Scalo give $r(4\ M_\odot) = 4.2$ and $r(0.1\ M_\odot) = 220$. Recent estimates of the pulsar birthrate by Lyne, Manchester, and Taylor (1982) indicate $r_{\text{of}} \sim 0.07$ (the birthrate is one pulsar every 20–50 yr in the Galaxy). The pulsar birthrate provides at least a lower limit to the birthrate of stars more massive than 4 $M_\odot$ and is consistent with Miller and Scalo's estimate.

In § VI we estimated a birthrate for outflows of $r_{\text{of}} = 10$, and in § V we argued that a massive star could not produce many outbursts leading to outflows. There is agreement that massive stars ($M > 4\ M_\odot$, say) have a pre–main-sequence (T Tauri) phase, but the birthrate $r(4\ M_\odot)$ is about 3 times smaller than our r_{of}. One could argue that a discrepancy of a factor of 3 is not too serious, but we feel that our r_{of} is probably still an underestimate, i.e., even nearby sources might be missed because of low surface brightness if the star is born in a region of low gas density or because the shock velocity gets too low quickly if the gas density is too large. The stellar birthrate $r(M_e)$ is a rapidly increasing function of decreasing M_e.

The number of outflow occurrences could then be easily explained if each star, irrespective of mass, produced one outflowing shell by means of its stellar wind; however, one should not expect to gain the full factor of $r(0.1\ M_\odot)/r(4\ M_\odot) \sim 50$ because low-mass stars are more likely to be produced in regions of lower density. Apart from these statistical arguments, the outflows in two clouds without large stellar luminosities also argue for low-mass stars. The question then is whether stars of low mass are physically able to produce such outflows.

If the only mechanism for producing outflow from a pre–main-sequence star (with energy outflow rate L_m) involved taking energy out of the radiative luminosity L (the likely mechanism for O-star winds), there would be difficulties for a star of low mass because L decreases very rapidly with decreasing M, and the lowest mass stars would produce little wind, since $L_m < L$ in this case; furthermore, the Kelvin-Helmholtz time scale t_{KH} (proportional to L^{-1}) would be long, and the lowest mass stars would not have time to reach the main sequence in a young molecular cloud. Observational data on pre–main-sequence evolution (Cohen and Kuhi 1979; Herbig 1982) at least allow the possibility of low-mass stars reaching the main sequence quickly.

Theoretically, $L_m \gg L$ is a possibility for low-mass stars if some fraction of the gravitational energy released by one parcel of matter accreting onto the protostar can be transferred into bulk kinetic energy of another parcel of matter moving away (the stellar outflow or "wind"). In practice, this energy transfer may have a number of intermediate stages. In a magnetic model (cf. Draine 1982), it may be that (i) gravitational energy is first stored in kinetic energy of rotation, (ii) rotational energy is converted into magnetic energy, and (iii) magnetic energy is converted into kinetic energy of overlying material (or the storage may reside in differential rotation; F. Shu, private communication). For our purposes the important aspect of such models is that (ii) and (iii) proceed without any mediation by radiative luminosity. No explicit models to date have combined step (i) with (ii) and (iii), and it is possible that the time scale for (i) is still controlled by the slow radiative energy leakage, so that it still takes the star the long time t_{KH} to get to the main sequence. Without offering any explicit model, we conjecture that it is possible to have all steps from gravitational energy release to outflow combined without the mediation of radiative luminosity. The relevant time scales might then be free-fall times, instability growth times, etc., which could all be extremely short compared with t_{KH}, and the duration of the outflow phase t_m (just before the star settles onto the main sequence) could easily be of the order of the times ascribed in Table 1 to the outflow.

We still have to consider the total energy E_m required for a stellar outflow episode, given in Table 1. In the class of models we are proposing, E_m would be some (hopefully appreciable) fraction of the total binding energy E_b of a star on the main sequence, $E_b \sim GM^2/R_{ms}$. The energy E_b decreases with decreasing M slightly more rapidly than M and is of order 2×10^{48} ergs for $M \sim 0.2\ M_\odot$. As seen in Table 1, the outflow energy E_m varies greatly from case to case; the lowest mass stars presumably would not be responsible for the outbursts with the largest individual E_m but could dominate the larger number of weaker outbursts. If the fraction E_m/E_b is independent of stellar mass M, then the stellar initial mass function and E_b combine in such a way that low-mass stars contribute just slightly more total kinetic energy to the interstellar medium than massive ones—about 3 times more from all stars than from stars with $M > 4\ M_\odot$.

The actual values of E_m and total mass m_m of the primary outflow required for a given observed high-velocity region depend somewhat on the assumed outflow speed v_m (E decreases and m_m increases with decreasing v_m). However, we conjecture that by analogy with ordinary stellar winds, v_m is of order the stellar surface escape velocity, which varies only from about 500 km s^{-1} for 0.2 $M_\odot$ to 1000 km s^{-1} for 10 $M_\odot$. We have assumed $v_m = 500$ km s^{-1} for Table 1, but a change by a factor of 2 or so would not matter much. As already suggested by Norman and Silk (1980), the energy input into clouds from these outflows is actually comparable to the energy needed to support the clouds. Norman and Silk relied mainly on rather energetic outflows from intermediate-mass stars to support the clouds, but we are suggesting that the observed sources of high velocity in molecular clouds may originate in relatively low-mass stars as well as more massive ones. Both the rate and distribution of sources in the clouds should be much easier to maintain uniformly if most of the outflows are associated with low-mass stars, even though the total energy input is raised only a factor of about 3 by our unorthodox suggestion of including stars with $M < 4\ M_\odot$.

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