A CONSTRAINT ON PRE-MAIN-SEQUENCE MASS LOSS*

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Abstract. The principal energy source of a pre-Main-Sequence (PMS) star is gravitational contraction. Mass ejection, regardless of its actual mechanism, in effect transfers gravitational potential energy from the entire star to the escaping matter. The virial theorem limits the efficiency of such a process. Theoretical PMS mass-radius relationships limit the total loss to a few tenths of the initial mass. The observed luminosities and estimated mass loss rates of T-Tauri stars are used to estimate the fraction of available energy expended on mass ejection. Actual losses appear to be much smaller than the theoretical limit in most cases. Only stars of emission line intensity classes 4 and 5 may be capable of significant mass loss.

1. Introduction

T-Tauri stars are believed to be in the pre-Main-Sequence (PMS) stage of evolution. A significant fraction of them show blue-shifted absorption features in their spectra. The simplest explanation for these features is that these stars are ejecting matter into space (Kuhi, 1964), although other interpretations are possible (Ulrich, 1976). This is the basis for the concept that the early Sun removed the solar nebula by the action of a strong 'T-Tauri solar wind' (Cameron, 1973a, 1977). Kuhi and Forbes (1970) and Ezer and Cameron (1971) modeled PMS evolution with empirical rates of mass loss. Each suggested that the Sun lost a substantial fraction of its initial mass during this stage.

There are few observational or theoretical constraints on this phenomenon. Its mechanism is unknown; the ejection does not appear to be a hydrodynamic expansion, as is the case for the present solar wind (Kuhi, 1964). Not all T-Tauri stars appear to be ejecting matter; it is not known whether the phenomenon occurs for all stars at some stage of PMS evolution, or is restricted to a particular class or mass range. Quantitative loss rates have been computed for only eight stars (Kuhi, 1964, 1966). Estimates of the total mass lost are based on these rates and theoretical PMS life times.

Williams (1967) suggested that the rate of energy expenditure on mass ejection would always be small compared with a star's luminosity. However, it is not clear from either theory or observation that this condition holds for PMS stars. We can place a stronger constraint on the total mass loss by considering the amount of energy available. Theoretical models of PMS stars (Iben, 1965) show that they do not begin hydrogen burning until they arrive at the Main Sequence. T-Tauri stars derive their energy from gravitational contraction. Regardless of the detailed mechanism, mass loss involves a decrease in the

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gravitational potential energy of the star, with the transfer of part of that energy to the escaping matter. The amount of mass which can escape is limited by the available energy, as shown below.

2. Energy Balance of a Contracting Star

A star of mass M and radius R has gravitational potential energy

$$\Gamma = -qGM^2/R, \tag{1}$$

where G is the gravitational constant, and q is a factor of order unity. For a polytrope of index n, $q = 3/(5-n)$. A fully convective star has $n \simeq 3/2, q \simeq 6/7$. For radiative energy transfer, $n \simeq 3, q \simeq 3/2$.

A change in the star's potential energy is

$$\mathrm{d}\Gamma = -\frac{GM}{R}\,[M\,\mathrm{d}q + 2q\,\mathrm{d}M - qM\,\mathrm{d}R/R]. \tag{2}$$

Suppose that the star ejects a mass element ($-\,\mathrm{d}M$). It gains an amount of energy

$$\mathrm{d}E = -CGM/R\,\mathrm{d}M, \tag{3}$$

where $C = (1 + v_\infty^2/v_e^2)$, $v_e = (2GM/R)^{1/2}$ is the escape velocity from the star's surface, and v_∞ the final velocity of the ejected matter. This energy is supplied by a decrease in Γ. The virial theorem requires that half of the change in Γ increase the star's internal energy. If a fraction f of the available energy is used to eject matter, then

$$\mathrm{d}E = -f/2\,\mathrm{d}\Gamma. \tag{4}$$

When $\mathrm{d}M < 0$, $\mathrm{d}\Gamma$ must be negative, requiring $\mathrm{d}R < 0$ and/or $\mathrm{d}q > 0$. In a fully convective star, q is constant. Setting $\mathrm{d}q = 0$, Equations (2)–(4) yield

$$\frac{\mathrm{d}M}{M} = \eta\,\frac{\mathrm{d}R}{R}, \tag{5}$$

where

$$\eta = \frac{fq}{2(C + fq)}. \tag{6}$$

If f is constant, then

$$\frac{M_2}{M_1} = \left(\frac{R_2}{R_1}\right)^{\eta}, \tag{7}$$

where the subscripts refer to the initial and final values. The semi-empirical mass loss rate assumed by Ezer and Cameron (1971) approximates a constant value of f.

When $f \neq 0$, the final mass can be arbitrarily small if the star can contract without limit. Fortunately, the range of R is limited. A collapsing protostar cannot attain hydrostatic equilibrium until its hydrogen has been dissociated and ionized. The gravitational potential energy released during hydrodynamic collapse must be sufficient to accomplish this, setting an upper limit to the radius of a stable PMS star (of Bodenheimer, 1972) of

$$R_{1_{\max}} \simeq 50(M/M_\odot)R_\odot . \tag{8}$$

Radiative losses during collapse will cause R_1 to be smaller. Larson's (1972) models of collapsing protostars produce maximum radii of about $10R_\odot$ for a wide range of masses.

A star formed in this manner is initially fully convective. It contracts with nearly constant surface temperature, tracing a nearly vertical 'Hayashi' track on the H-R diagram. If mass ejection is a property of the convective phase, the radius at the bottom of this track is appropriate for R_2 in Equation (7). In the range $M < 5M_\odot$, Iben's (1965) models have $R_2 \simeq 1.2(M_2/M_\odot)^{1.8}R_\odot$.

Near the bottom of the Hayashi track, the star begins to develop a radiative core. The surface temperature increases, and the star moves to the left on the H-R diagram. For M in the range of $M_\odot$ to $1.5M_\odot$, this occurs at nearly constant R, while q increases. If the mass loss is small during this stage, we may set $\mathrm{d}R = 0$ in Equation (2), giving

$$\frac{\mathrm{d}M}{M} = \frac{-f\,\mathrm{d}q}{C+fq}. \tag{9}$$

For constant f, this gives

$$\frac{M_2}{M_1} = \left[\frac{C+fq_1}{C+fq_2}\right]^{1/2}. \tag{10}$$

In the change from convective to radiative structure, q goes from 6/7 to 3/2. The greatest mass loss occurs for $C=f=1$; this gives $M_2/M_1 = 0.86$. Since mass loss effectively ceases on the Main Sequence, f should be small at this stage; $f = 0.1$ gives $M_2/M_1 = 0.97$. For solar-type stars, it appears that any significant mass loss is confined to the convective stage. For more massive stars, R and q both change on the radiative track, and the energy balance must be done numerically.

We must still determine an appropriate value of η for use in Equation (5). An absolute upper limit is found by setting $C=f=1$. This corresponds to a non-luminous star which uses all available energy to eject matter with the minimum energy for escape. When $q = 1$, this case gives $\eta_{\max} = 1/4$. When the rate of energy expenditure on mass ejection equals the luminosity, i.e., $f = 1/2$, then $\eta = 1/6$. Figure 1 shows the fraction of initial mass lost as a function of R_1/R_2, according to Equation (7). Loss of more than half of the initial mass is effectively impossible. Much lower limits on η and the mass ejected may be set by observations of T-Tauri stars, as described below.

This analysis is valid only for the case of spherical symmetry. Cameron's (1978) model of an accretion disk uses the inflow of matter to drive mass loss from the surface of the disk. The problem is more complex, but a similar energy balance may in principle be used to place some constraints on the disk's mass and structure.

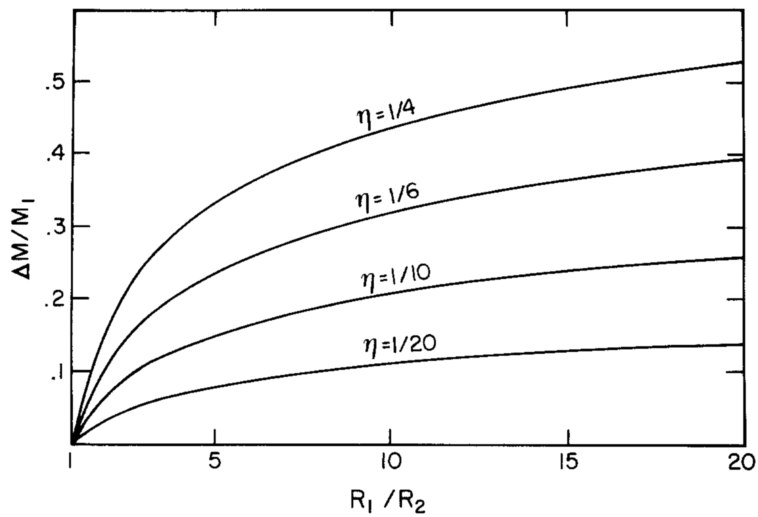

Fig. 1. Fraction of initial mass lost, as a function of the ratio of initial and final stellar radii, according to Equation (7).

3. Other Energy Sources

Thus far, we have considered only gravitational contraction as an energy source. The (unknown) mechanism for mass ejection may involve magnetic fields (Kuhi, 1964), turbulence or acoustic waves (Cameron, 1973a), and/or rotation. However, these can be shown to have little effect on the star's overall energy budget. Suppose, e.g., that it possesses a magnetic field. The star's initial magnetic energy must be less than the magnitude of its gravitational energy, $\simeq GM_1^2/R_1$, or it will not be stable. This energy is small compared with the total released during contraction. If the magnetic field is compressed during this process, its energy increases; however, this energy is derived from the star's gravitational potential energy. If the magnetic energy is involved in the ejection of matter, it merely acts as a 'middleman' in the process. The same argument can be applied to turbulent or rotational energy. Aside from a small initial contribution, they are derived from the star's contraction, and do not affect the derivation of Equation (5). This can be shown rigorously; in the formalism of the virial theorem, rotational, turbulent and magnetic terms can be treated as part of the internal energy (Cox and Giuli, 1968).

Deuterium burning can be a significant energy source for low-mass PMS stars. The total amount of D is proportional to M, while $\Gamma \propto M^2$. Using the solar system's initial D/H ratio (Cameron, 1973b), the energy released by D burning is of the order of $0.05(M/M_\odot)$ times the gravitational energy. There is no reason to believe that this contribution should be more effective for ejecting matter, but it can, in principle, be important for stars with $M < M_\odot$.

4. Observational Constraints

We may try to determine f directly from observed values of M, R, $\mathrm{d}M/\mathrm{d}t$, and luminosity. All of these quantities are poorly known, and their determination complicated by the variability of these stars, but they may at least establish the order of magnitude of f. It is generally assumed, and consistent with Kuhi's (1964) models, that the ejected matter barely escapes ($C = 1$), but we shall consider the more general case.

Let the star's actual luminosity be L_*, which may differ from the observed value, L_{obs}. We define $\dot{E}_0 = -GM/R\ \mathrm{d}M/\mathrm{d}t$ as the minimum rate at which energy is supplied for mass ejection, and $\dot{E} = C\dot{E}_0$. If L_* is known, and C is assumed to be unity but is actually larger, then it can be shown that f is underestimated by the factor $(C\dot{E}_0 + L_*)/(C\dot{E}_0 + CL_*)$, and η is overestimated by the factor $[(C + q)\dot{E}_0 + L_*)]/[(1 + q)\dot{E}_0 + L_*]$. The assumption that $C = 1$ provides an upper limit to η.

Suppose that a circumstellar cloud is heated by excess energy of the ejected matter (this requires $C > 1$), and that this cloud contributes to L_{obs}. Then $L_{\mathrm{obs}} = L_* + (C - 1)\dot{E}_0$, and the true value of f is

$$f = \frac{\dot{E}}{\dot{E} + L_*} = \frac{C\dot{E}_0}{C\dot{E}_0 + L_{\mathrm{obs}} - (C - 1)\dot{E}_0} = \frac{C\dot{E}_0}{\dot{E}_0 + L_{\mathrm{obs}}}, \tag{11}$$

which is C times the value, f_0, computed by assuming that $L_* = L_{\mathrm{obs}}$ and $C = 1$. However, the actual value of η is

$$\eta = \frac{Cf_0q}{2(C + Cf_0q)} = \frac{f_0q}{2(1 + f_0q)}, \tag{12}$$

which is the same as that computed by assuming that $L_* = L_{\mathrm{obs}}$ and $C = 1$. Therefore, η is not overestimated by using the observed luminosity, if it can be accurately determined, and the quantities which determine $\dot{E}$ can be deduced.

5. Results and Discussion

Table I lists properties of those stars for which Kuhi (1964, 1966) computed rates of mass loss. Recent observations over a broader spectral range (Imhoff and Mendoza (IM), 1974; Rydgren, Strom, and Strom (RSS), 1976) yield luminosities which differ from Kuhi's values and imply corresponding changes in R and M. Wherever these sources state L, R, or M, their values are used. Missing values of R and L are computed from the relation (Kuhi, 1964)

$$\log (R/R_\odot) = 1/2 \log (L/L_\odot) - 2(\log T_e - 3.76). \tag{13}$$

When the effective temperature T_e was not stated, it was derived from the spectral type, using Johnson's (1966) calibration. RSS were unable to determine a spectral type for RW Aur because of strong spectral veiling. Herbig (1977) has determined spectral types for several T-Tauri stars with strong emission that were previously thought to be G-type stars;

TABLE I
Properties of T-Tauri stars with mass loss

Star	Source[a]	$M/M_\odot$	$R/R_\odot$	$L/L_\odot$	$-dM/dt$ ($10^{-7} M_\odot \text{yr}^{-1}$)	f ($q=1$)	η	Emission intensity[b]
T Tau	K4	0.6	4.65	5.35	0.35	0.026	0.013	2
	IM	2.5	6.2	18.2	0.65	0.042	0.020	
	RSS	2.5	6.2	24.0	0.65	0.032	0.016	
RY Tau	K4	0.9	3.25	3.4	0.31	0.072	0.034	2
	IM	2.7	6.7	33.9	1.32	0.046	0.022	
	RSS	2.25	4.2	16.2	0.52	0.050	0.024	
GW Ori	K4	1.3	8.64	22.1	0.35	0.007	0.0036	2
	IM	3.0	8.22	51.3	0.32	0.007	0.0035	
SU Aur	K6	1.21	5.68	32.3	0.25	0.005	0.0025	1
	IM	2.0	3.6	8.9	0.10	0.019	0.009	
	RSS	1.7	3.0	7.4	0.07	0.016	0.008	
RW Aur	K6	1.16	2.46	5.66	1.11	0.222	0.091	5
	IM	1.5	2.3	4.0	0.97	0.325	0.122	
	RSS	1.5	4.72	7.6	4.08	0.345	0.128	
RU Lup	K4	1.42	2.95	2.63	1.42	0.445	0.154	5
AS 209	K4	0.81	2.94	2.18	0.65	0.202	0.084	4
Lk Hα 120	K4	4.1	11.16	68.5	5.85	0.088	0.041	4

[a] K4 = Kuhi (1964)
K6 = Kuhi (1966)
IM = Imhoff and Mendoza (1974)
RSS = Rydgren, Strom, and Strom (1976)

[b] Herbig and Rao (1972)

these new spectral types range from mid K to early M. Herbig's revised types and the scarcity of G-Type T-Tauri stars led to RSS to suggest that RW Aur is most likely a K or early M star. I have assumed it to be K5 for this calculation. For IM and RSS, M was estimated from a star's position on the H-R diagram with respect to Iben's (1965) theoretical PMS tracks. Kuhi's stated masses are not always consistent with Iben's results. Figure 2 shows the positions of five stars according to IM.

Kuhi's mass loss rates were calculated from the estimated density and velocity of the ejected matter, and the surface area of the star. Therefore, I have scaled Kuhi's values of dM/dt as R^2 for the stellar parameters of IM and RSS (neglecting possible effects of temperature and surface gravity on the calculated rates). Bodenheimer (1972) suggested that upward revisions of L would imply shorter contraction times and smaller total mass losses. However, a change in L generally implies a similar change in surface area, and hence in dM/dt. The value of f is, therefore, not very sensitive to luminosity. Still, all of these stars are variable, and the quoted values of L and dM/dt were generally determined at different times. Kuhi's value of dM/dt for each star is the mean of several determinations, which vary by as much as a factor of three. Obviously, all of the listed quantities are very uncertain.

Figure 3 shows the variation of f with Herbig and Rao's (1972) emission line intensity class. Of the three stars with $f > 0.1$, all are of class 4 or 5. Their high values of f are

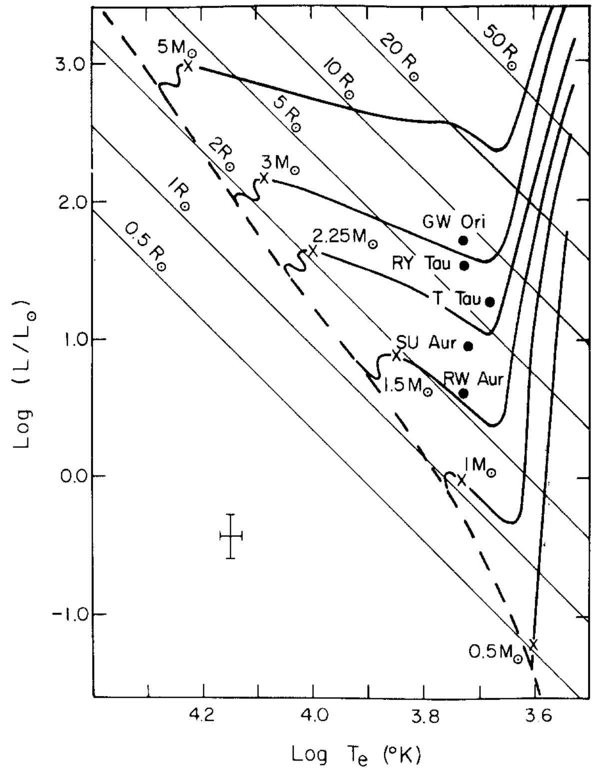

Fig. 2. Positions of five T-Tauri stars on the H-R diagram, as determined by Imhoff and Mendoza (1974). 'Error bar' is maximum difference from determination by Rydgren *et al.* (1976) for these stars only. Actual uncertainties are presumably much larger. PMS tracks for various masses are from Iben (1965); X on each track marks the point at which 10% of the star's energy production is due to hydrogen burning. Dashed line: zero-age Main Sequence.

consistent with their level of activity, but interpretation of their spectra is difficult. Observations of RU Lup allow a wide range of values for R, L, and M; any model is complicated by the possibility of a large and variable circumstellar extinction (Gahm *et al.*, 1975). The spectral types of AS 209 and Lk Hα 120 are unknown (Herbig and Rao, 1972). RW Aur has an unusually complex spectrum (Gahm, 1970a). Gahm (1970b) reexamined its line profiles, and concluded that Kuhi had overestimated its mass loss rate by about a factor of two; this would imply $f \simeq 0.15$, $\eta \simeq 0.07$. Similar analyses should be performed for the other stars of classes 4 and 5. These objects, which appear to be the only ones capable of significant mass loss, represent only a small fraction of PMS stars. Herbig and Rao list 36 of class 4, and 12 of class 5, out of a sample of 323 stars. Apparently, Kuhi's selection favored the most active objects.

If correctly assigned by IM, RW Aur is on the radiative track. In that case, its present level of activity is probably a transient event. If it is of a later spectral type, as suggested by RSS, it would be on the convective track. Its high Li abundance (Zappala, 1972) is

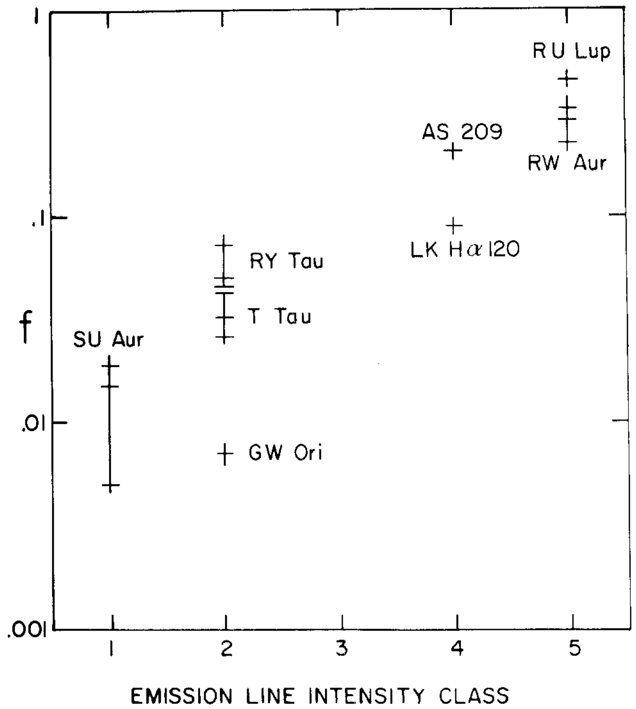

Fig. 3. Log f plotted against Herbig and Rao's emission line intensity class. Each cross-bar is a determination from the sets of parameters given in Table I.

consistent with a convective state, since Li destruction would occur nearer the ZAMS. RW Aur has a fainter companion, classed as type M (Herbig, 1962; Joy and Abt, 1974) or K3e (Herbig and Rao, 1972). If they are coeval, the fainter component should have a lower T_e and smaller mass (probably $0.5–1.0 M_\odot$). Iben's calculations would imply an age of about 10^6 y for this system, with both components convective.

One is tempted to identify stars of the highest emission line intensity classes as being fully convective. However, Cohen and Kuhi (1976) report a number of stars which appear to be on convective tracks; several of these are listed by Herbig and Rao as being of classes 1 or 2. It is not known whether any of these stars are losing mass.

6. Summary

The total amount of mass which may be lost from a PMS star is limited by the energy released by gravitational contraction, regardless of the mechanism of ejection or its instantaneous rate. For a solar-type star, mass loss on the radiative track will not exceed a few percent. Larger losses are possible on the convective tracks. If the star's radius decreases by a large factor, the fraction of initial mass lost is comparable to the fraction f of available energy expended on ejection. This quantity appears to increase with emission line intensity; for stars of classes 4 and 5, f may exceed 0.1. However, quantitative estimates of their mass loss rates are very uncertain, due to difficulties in interpreting their spectra. Moreover, these stars represent only a small fraction of PMS objects. Quantitative calculations of mass loss rates have been performed for only eight stars, more than a decade ago. Such analysis must be extended to a much larger sample, using modern techniques, in order for the concept of a 'T-Tauri solar wind' to be meaningful.

Acknowledgements

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