Interstellar Astrophysics
Summary notes: Part 5

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Note: Figure numbers refer either to the chapter and figure number (N-n) in Freedman and Kauffman, or to the Dyson and Williams textbook.

5 Star formation in the interstellar medium

Interstellar gas and dust provides the raw material out of which stars are made. The disc of our Galaxy, where most of the ISM material is concentrated, is a site of ongoing star formation.

We believe that star formation results from the collapse under gravity of large diffuse interstellar clouds. A simple picture for star formation considers a spherical cloud of radius, R, mass, M, isothermal temperature, T, and density ρ, and looks at the competing forces acting on this material.

In hydrostatic equilibrium the outward force due to the gas pressure (which tries to expand the gas) is exactly balanced by the inward gravitational force (trying to collapse the gas). In stars like the Sun, these two forces are in balance and the star remains stable and has a constant radius.

The simple equation of Hydrostatic Equilibrium (HE) gives:

$$P = -\rho \, G \, \frac{M}{R}$$

where P is the pressure and G the gravitational constant.

If the l.h.s. of this equation is $>$ r.h.s, the gas would expand and the radius increase. If the l.h.s. is $<$ r.h.s. then gravity $>$ gas pressure and the object will collapse and r will decrease.

Now in the idealised case, the gas pressure, $P = \rho kT$ (k is the Boltzmann constant), so if we want to collapse the object we need the gas pressure to be as low as possible, and thus we need low temperatures. Also we would like the gas mass to be as large as possible to maximise the gravity. Thus we expect the gravitational collapse of a cloud to be favoured in cool, dense regions of the ISM. Star formation sites should therefore be associated with dark nebulae (like the Horsehead nebula or Barnard objects – see Fig.

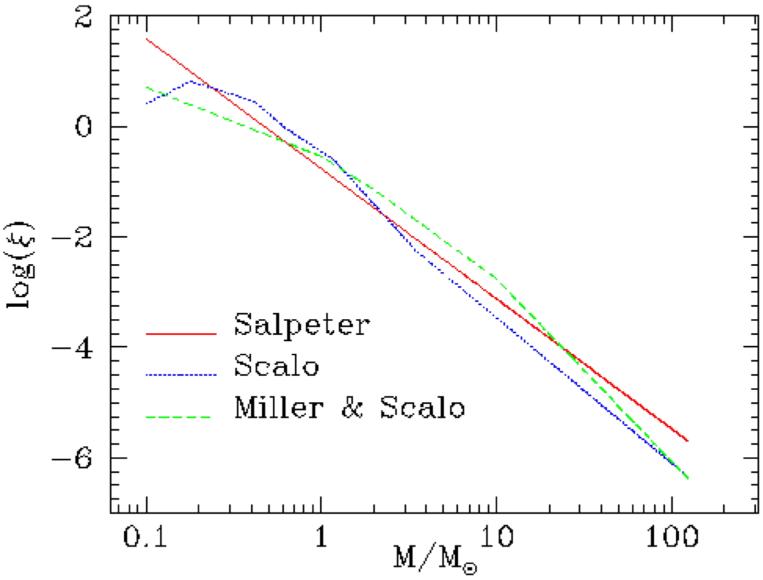

Figure 1: Three different observationally derived initial mass function (IMF) parameterisations. Plotted is the number of stars (in log space) on the y-axis, vs. the stellar mass (also in log) on the x-axis.

20-3). Other small, dense dark nebulae are known as Bok Globules (see Fig. 20-8) where $\rho \sim$ 100–10 000 particles cm^{-3} and T is low ($\sim$ 10 K). A typical Barnard object has $R \sim$ 10 pc, and contains about 10^3–10^4 M$_\odot$ of material. A typical Bok Globule is about 1/10th of this size.

One can use the HE equation, to show that there is a minimum mass, for a given T and density ρ, for gravitational collapse to occur. This is known as the Jeans' mass, M_J. It is found that M_J is proportional to $T^{3/2}\,\rho^{-0.5}$. For typical values of T and ρ, one finds that $M_\mathrm{J} \sim 10^5$ M$_\odot$.

Thus for the normal diffuse ISM, the Jeans' mass is very large ($10^5 = 100\,000$ M$_\odot$).

Since stars have masses of typically only a few solar masses, this implies that a large collapsing gas cloud must break up into smaller "parcels" of gas before star formation can begin – a process called **fragmentation**. It turns out that models of collapsing clouds, including the effects of rotation and magnetic fields, naturally predict cloud fragmentation, with the smaller clumps of material forming protostars. Within a large cloud one would expect to produce large numbers of such clumps, and protostars. This leads naturally to the formation of a "stellar nursery", and therefore the formation of star clusters with a range of star masses. The distribution of stars of certain masses within a star-formation region is known as the initial mass function (IMF), and can be measured observationally by counting the number of stars of each mass. Fig. 1 shows the observationally derived IMFs from a number of different studies, and shows that the mass function favours the low-mass stars like the Sun, rather than very high mass (OB) stars.

If the initial cloud mass $>M_\mathrm{J}$, then the cloud will collapse under its own gravity, in what is termed a free-fall collapse. The typical timescale for such a collapse is $\sim 10^7$ years. As the cloud collapses the density, ρ, increases and M_J decreases. Therefore, as the cloud collapses, the sizes of the fragments decreases.

5.1 Pre-main sequence star formation: evolutionary tracks on the H-R diagram

Individual collapsing clumps of material (formed in the gas cloud fragmentation) will be relatively cool and several times larger than our Solar System. The pressure is still too low to overcome gravity and the the protostar continues to collapse. As it contracts, some of the gravitational potential energy is converted into thermal energy. Thus the gas heats up, and the protostar begins to emit low-energy radiation at mm and far-IR wavelengths. At this phase, after a few thousand years of contraction, the surface temperature of the protostar reaches about 3 000 K, and the object has a luminosity of 1–10^4 $L_\odot$ – depending on the mass of the protostar. A 1 $M_\odot$ protostar has $R \sim 20$ $R_\odot$ and $L \sim 100$ $L_\odot$. (N.B.: the protostar luminosity is NOT due to nuclear fusion in the core – this starts much later when the object becomes a proper main sequence star. At this point it is simply the result of the release of gravitational energy due to collapse).

Computer simulations of the star formation process allow us to follow how the temperature and luminosity of the protostar changes with time as the collapse continues (as a function of the mass of the protostar) and thus we can plot an pre-Main Sequence evolutionary track on the Hertzsprung-Russell (H-R) diagram.

In 1961 Hayashi showed that there is a minimum temperature cooler than which hydrostatic equilibrium cannot be maintained; this boundary, corresponding to a temperature around 4 000 K, exists on the right-hand side of the H-R diagram. Protostellar clouds cooler than this will contract and heat up until they reach the Hayashi boundary. Thus, the beginning of the track on the H-R diagram represents the point at which hydrostatic equilibrium begins to hold.

For much of the initial collapse, energy is transported from the inner to outer regions of the protostar by convection, warming its surface. As the radius of the protostar decreases, the luminosity decreases at almost constant surface (effective) temperature. On the H-R diagram this change in L at $\sim$constant T thus gives a nearly vertical track known as a convective Hayashi evolutionary track (Fig. 2). The protostar is travelling along the Hayashi boundary.

Protostars with a wide range of masses (roughly 0–4 $M_\odot$) are all observed to have roughly the same T ($\sim$4 000 K), meaning that they must all have a Hayashi convective phase.

If the protostar is massive enough (>0.8 $M_\odot$), eventually the internal energy transport becomes dominated by radiative energy transport (rather than convection). As the radius continues to decrease, the T of the protostar now increases at roughly constant luminosity. This gives a roughly horizontal track on the H-R diagram called the Henyey radiative evolutionary track.

Eventually the central, core temperature of the protostar reaches a sufficiently high value (typically $> 10^7$ K) for core hydrogen-burning fusion reactions to begin. This produces a large increase in energy output, and the resulting pressure increase halts any further

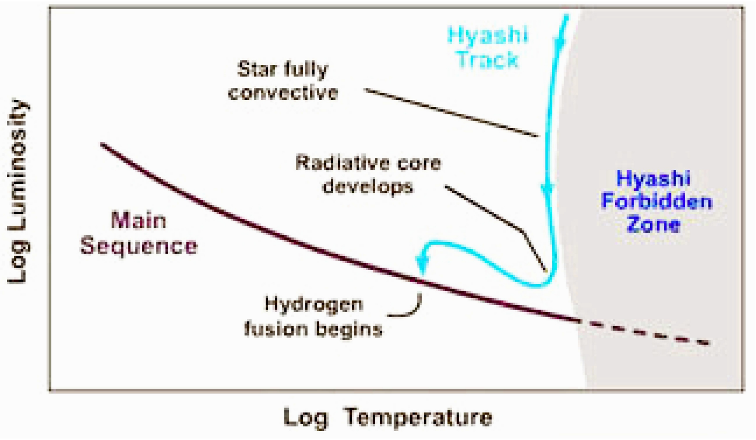

Figure 2: A simplified model evolutionary track on the H-R diagram for a 1 $M_\odot$ pre-main sequence (proto) star.

collapse. After a period of adjustment, where the radius and temperature change as the star balances the energy generated by fusion with its gravity, it enters the Main Sequence (MS). The luminosity at which the star switches from convective to radiative is larger for high mass stars than low mass stars, and essentially determines the point on the H-R diagram where the star will become a Main Sequence star and the time it takes to get there (see Fig. 18-10). Typical timescales for protostars to reach the main sequence are: $\sim10^7$ years for a 1 $M_\odot$, and $\sim10^5$ years for a 15 $M_\odot$ star.

The internal structure of early main sequence stars for different mass stars is shown in Fig. 18-12. Very low mass stars (<0.4 $M_\odot$) have convective cores. Intermediate mass stars have radiative cores a convective envelopes. The most massive stars (>4 $M_\odot$) have convective cores and radiative envelopes. Where convection or radiation takes place has to do with the density of the different layers, making the two processes more or less efficient at different depths.

There is a lower limit to the mass of a MS star of ~0.1 $M_\odot$. Below this, the core temperature never becomes hot enough for H-burning to begin (there being insufficient gravitational energy available to heat the gas to the required temperature). An object below this limit is called a brown dwarf.

There is also believed to be an upper limit to a MS star mass of $\lesssim100$ $M_\odot$. Above this, the star's luminosity is greater than the so-called Eddington Limit, where the outward force exerted by the radiation on the gas is larger than the inward gravitational force[1], and the star blows itself apart.

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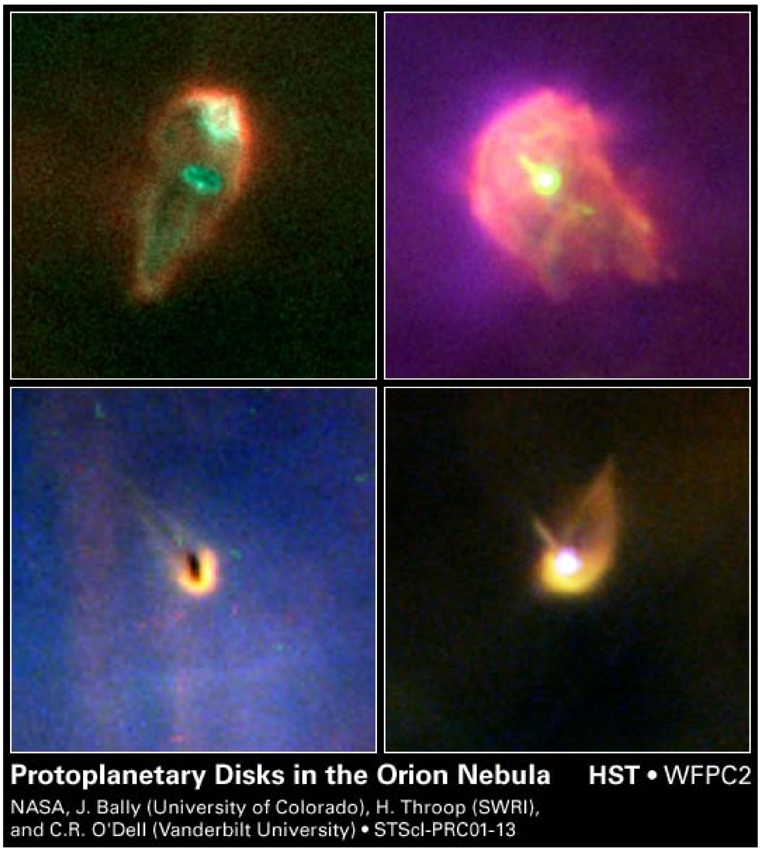
[1] The Eddington Limit also applies to other types of astrophysical objects, like AGN (black-hole accretion disks).



Protoplanetary Disks in the Orion Nebula **HST** • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University) • STScI-PRC01-13

Figure 3: Protoplanetary discs (proplyds) observed with *HST* in the Orion nebula.

5.2 Observational signatures of protostars and pre-main sequence evolution

The formation and collapse of protostars is not truly spherically symmetric; there is a lot of evidence that the collapse involves:
(i) the generation of an accretion disc around the protostar, and
(ii) material ejection into space so that the final mass of the MS star is less than the mass of collapsing protostar clump.

Material ejection is evident in the T Tauri stars, which are now recognised as protostars. The optical spectra of T Tauri stars show emission lines and varying optical luminosities (sometimes on timescales as short as days). Typical parameters of T Tauri stars are mass $\sim 3\ \mathrm{M}_\odot$, age $\sim 10^6$ years, $T_{\mathrm{eff}} \sim 4\,000$ K, and luminosity $\sim 100\ \mathrm{L}_\odot$. The emission lines are often Doppler shifted, indicating gas ejection at $\sim 80\ \mathrm{km\,s^{-1}}$. The emission lines are produced in low density gas outflowing at rates of $\sim 10^{-7}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$. Thus over the lifetime of the protostar ($\sim 10^7$ years), about $1\ \mathrm{M}_\odot$ of material can be ejected!

5.2.1 Protoplanetary discs

A protoplanetary disc (or proplyd, if you must!) is a rotating disc of matter surrounding a young newly formed star, including gas and dust, from which planets may eventually form or be in the process of forming. They have radii $\lesssim$1 000 astronomical units (AUs) and are cool. Only the innermost regions reach temperatures >1 000 K. They are very often accompanied by jets (see below). "Proplyd" is a very basic, purely observationally-motivated classification, and as such is used to refer to proto-stars in a range of evolutionary stages.

Protoplanetary discs have been observed around several young stars in our galaxy, the first being found around the star Beta Pictoris in 1984. Recent observations by *HST* have discovered a large number protoplanetary and planetary discs to be forming within the Orion Nebula (see Fig. 3). Their shape is formed by interactions between the disk and the strong radiation field and winds from nearby OB stars. Astronomers have also discovered large discs of material, which may themselves be protoplanetary discs, around the stars Vega, Alphecca and Fomalhaut, all of which are very close to the Sun.

5.2.2 Protostar jets

In the 1980s it was found that many protostars, including T Tauri stars, are losing mass by the ejection of material along two narrow, oppositely directed jets – a phenomenon known as bipolar outflows. This material, out-flowing at speeds of $\sim$100 $\mathrm{km\,s^{-1}}$, can collide with ambient ISM gas/dust clouds and produce knots of hot, ionised gas that glow with an emission spectrum. These are known as Herbig-Haro (HH) objects. Fig. 18-14 shows one Herbig-Haro object in Orion. Repeat observations show that HH objects can change the position of their knots, brightness and shape over timescales of years, indicating the dynamical character of these bipolar outflows.

In addition to these ejections the protostar can also gain some mass by the process of accretion. The main concepts here are: (i) as the protostar nebula contracts, it spins up and flattens into a disc, with the protostar at the centre (this is analogous to the flattening of the Solar nebula, out of which the planets formed). (ii) particles orbiting the protostar in the disk collide with each other, lose energy and spiral into the protostar, adding to its mass. This is known as a circumstellar accretion disc.

Fig. 18-15 shows an *HST* infrared image of such a disc (viewed edge on) – red emission is from ionised gas and green emission is scattered light from dust particles in the disc.

The basic physical model for jets involves magnetic fields in the protostellar nebula. Fig. 18-16 gives some of the basic ideas. As material in the circumstellar disc falls inwards, it drags its magnetic field with it (the magnetic field can be thought of as being "frozen" into the gas – i.e. it moves with it). Parts of the disc at different radii orbit the protostar at different speeds (referred to as differential rotation), twisting the magnetic field lines into two helix shapes on either side of the disc. These helices act as channels that guide outflowing material away form the protostar forming the two jets.

(N.B.: interactions between the protostar, disc, and jets, may help to slow down the rotation of the protostar, explaining why the final rotation speeds of main sequence stars are often less than the rotation speeds of the protostar "parents").

5.3 The classification of protostars

Our lack of knowledge of star formation processes has led to an empirical classification of the evolutionary phases of low-mass protostars into four classes: 0, I, II, and III. These describe the amount of material available for accretion versus the mass of the central object, providing the evolutionary status of the system. Class 0 objects are the young and dusty envelopes that feed the central objects and their protoplanetary discs, and are characterised by temperatures of 15–30 K, and by the presence of a highly collimated jet. Due to the heavy obscuration from the large amounts of circumstellar material, they have been detected and studied only at far-IR and millimeter wavelengths.

Class I sources are still embedded in copious amounts of material, and the ejection of matter appears to be less violent than in class 0. The outflows/jets begin to illuminate the surrounding dusty envelope. Class II corresponds to T-Tauri stars; the stellar radiation becomes visible in the UV/optical, whereas the (accretion) disc emits strongly in the near/mid-IR. Class III objects represent the stage just before the Main Sequence. The infalling envelope clears, the outflow stops and the disc becomes optically thin (i.e. near-transparent to radiation). The accretion disc becomes a debris disc, and planetary formation follows.

Very recently (and this is not widely accepted), a new evolutionary stage has been identified and termed class -1, representing what is known as a pre-protostellar core. These objects, usually part of larger clouds, are characterised by "inside-out" collapse (the inside collapsing faster than the outside) traced through mm/sub-mm observations.

5.4 The triggering of star formation

We have seen how within our own galaxy, the sites of new star formation are coincident with the location of the giant molecular clouds and the spiral arms (Fig. 18-21). The passage of a spiral arm through a region therefore induces star formation. However, anything that can compress interstellar clouds has the capability of triggering the formation of new stars. One of the most dramatic compressive events is caused by a supernova explosion, when material is expelled into space at speeds of several $1\,000$ km s^{-1}. Nebulae made out of this material are called supernova remnants (SNRs), such as the one shown in Fig. 18-24. The expelled material typically has speeds greater than the (local) speed of sound in the interstellar medium, producing a shock wave that dramatically compresses the medium through which it passes.

When the expanding shell of a SNR encounters an interstellar cloud, it compresses the cloud gas and stimulates new star birth. Fig. 18-22 shows an example of this kind of situation: the new star formation is taking place along a luminous arc of gas, and shows significant T Tauri activity. Some astronomers have proposed that the Sun was one of a number of stars formed when the passage of a nearby supernova shock wave compressed a cloud of interstellar gas.

Other processes can also trigger star formation. For example, the collision between two interstellar clouds can create new stars. Compression occurs at the interface between the two colliding clouds and vigorous star formation ensues. Similarly, stellar winds from a cluster of OB-type stars may exert a strong enough pressure on interstellar clouds to cause compression and star formation (see Fig. 18-23).