Where Are Stars Born?

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Introduction

The twentieth century saw great advances in our understanding of the workings of the stars mankind had studied for many centuries. Through the advent of nuclear chemistry the source of a star's energy, nuclear fusion, was exposed, solving the age old question of "Why does the Sun shine?" Analysis of starlight has become a fine art, allowing science to dissect the star and catalogue its composition, size, temperature, atmosphere, magnetic field, and other properties. The development of high speed, general purpose computers has allowed the numerical solution of equations that govern the a ball of gas the size of a star and explain many observed phenomena. These models have allowed us to probe the evolution of stars toward their end, and back toward their creation. With the application of improving optical and electronic sensor systems, and space based equipment, astronomers have been able to find the results of stellar evolution. Until recently science had not truly uncovered the birthplace of stars. Even now, there are some questions that remain unanswered.

This paper aims to briefly cover the topic of stellar formation, the locations in which it happens, and the tools astronomers use to study these regions and process.

Finding The Birthplace

The search for regions of stellar birth is rooted in theory. Early in the twentieth century, Sir James Jeans published an analysis of conditions required for a cloud of gas to collapse under the influence of its own gravity. Starting with an idealised sphere of gas, and using the virial theorem as the key to understanding the physics, Jeans arrived at an equation for the minimum mass required to cause collapse:

$$M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

where k is Boltzmann's constant, T is the temperature in Kelvin, G is the universal gravitational constant, μ is the average molecular mass in terms of the weight of a hydrogen atom m_H, and ρ_0 is the starting density of the cloud. This mass is now known as Jeans Mass. If the mass of the cloud M_C exceeds M_J then the cloud will collapse, otherwise it is stable: this is the Jeans Criterion.

Despite Jeans' simplifying assumptions, such as discounting rotational effects, the equation told astronomers that collapse would be most likely in regions of low temperature and high density, where M_J is minimised.

Observational astronomers knew of clouds of gas and dust in the heavens. They could see them in reflection and emission nebulae, the reddening of stellar spectra, and the dark, apparently empty, voids obvious in some areas of the sky.

The Interstellar Medium and Diffuse Clouds

The space in between stars is very sparsely populated with atoms and molecules of various sorts; the interstellar medium (ISM). Hydrogen makes up the bulk of this material ($\sim$70%) and helium the remainder with traces of elements such as oxygen, carbon, silicon, approximately 120 simple molecules [1, 2], and dust. The ISM hydrogen appears in molecular (H_2) and ionised (H II) forms, but mostly in neutral atomic (H I) form. As hydrogen is the key ingredient in a star this was where much research concentrated. The following paragraphs briefly discuss each of these components.

Ionised Hydrogen (H II). The most conspicuous clouds in the galaxy are the glowing nebulae such as the Orion Nebula (M42) or Lagoon Nebula (M8). The distinctive spectral signature of strong Balmer lines, particularly the pink 656.3 nm line, in these clouds showed the dominance of ionised hydrogen in their composition. Some nebulae with greenish tinges betrayed the presence of doubly ionised oxygen (O III) emitting at 495.5 nm and 500.7 nm These emissions were typical of gas at high temperature and low density, precisely the opposite of the expected conditions for star formation.

Neutral Hydrogen (H I). Atomic hydrogen clouds proved more difficult to detect because hydrogen's electron is tightly bound in the lowest energy state. However, both charged particles in a hydrogen atom possess a quantum characteristic called spin, that can be used to detect them. When the particles spin in the same sense the atom has slightly higher energy than when the spins are opposite (anti-sense). Rarely, an atom's particles will spontaneously flip from the high energy state to the other, emitting a photon at $\lambda = 21$cm in the process. These emissions are detectable using radio-telescope equipment. Studies of diffuse neutral hydrogen clouds found temperatures in the range of 30-80K, 100-800 atoms per cubic centimetre, and total masses between 1-100 $M_\odot$. Applying the Jeans Criterion, $M_J \sim 1500 M_\odot$, to these clouds quickly eliminated the possibility of collapse in these regions; there was insufficient mass.

Molecular Clouds. The darker clouds of molecular hydrogen (H_2), however, told a different story. In the central regions of molecular clouds, M_C 10 to 1000 $M_\odot$, the temperature is around 150 K and the Jeans mass is approximately $17 M_\odot$ [3, §12.2]. Under these conditions collapse of the cloud could occur, so molecular clouds were a potential site of star formation.

Molecular Clouds

Molecular clouds come in a range of sizes. At the upper extreme are giant molecular clouds (GMC), which contain a scattering of dense, warmer regions, called cores. At the small end of the scale are very dark, nearly spherical, nebulae called Bok globules (after Bart Jan Bok who studied them in detail). Intermediate to GMCs and Bok globules are Barnard objects, named after Edward Barnard who first catalogued them, which look like Bok globules with an extended envelope. Thousands of molecular clouds have been identified in the Milky Way through systematic surveys such as those done by Scoville and Solomon [4] and more recently Dame, Hartmann, and Thaddeus [5]. Barnard 68 (B68), actually considered a Bok globule, is shown in Figure 1. It is approximately 500 light-years distant and half a light year across. B68 is believed to be on the verge of collapse [6].

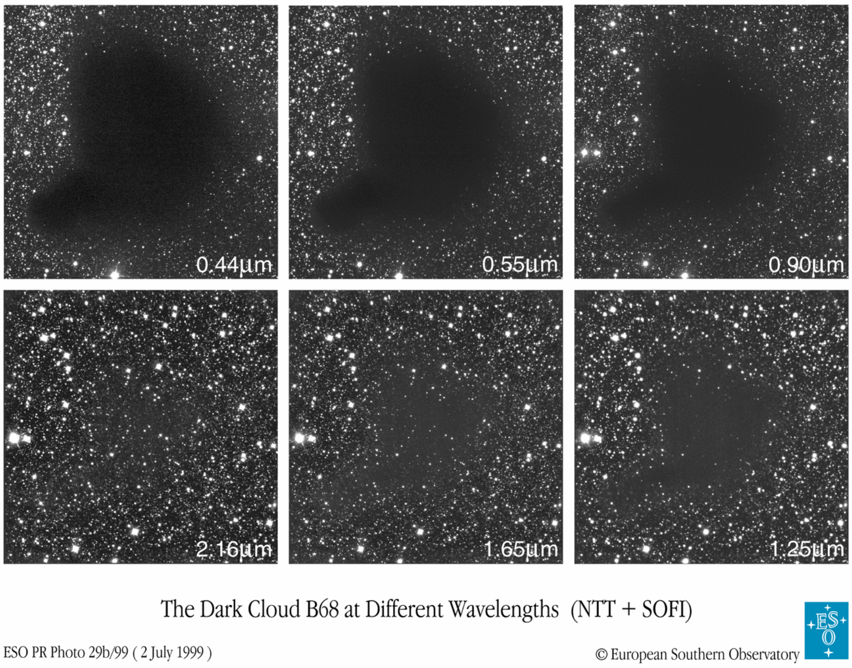

Figure 1: Barnard 68 at differing wavelengths from 0.44μm blue to 2.16μm IR. The cloud is nearly transparent to IR but offers $\sim$34 magnitudes of attenuation to visible light. Even at IR wavelength there remain opaque regions. Image credit European Southern Observatory (ESO).

The study of the interior of molecular clouds, and potentially young stellar objects (YSO) within, is made difficult by the interaction of gas and dust with emitted radiation. At visible wavelengths astronomers can only see objects in outer fringes of the clouds: deeper objects are completely obscured by dust which scatters light (Mie scattering). Differing degrees of penetration are available at different wavelengths as clearly shown in Figure 1. For photographic purposes, the cloud is best penetrated at infrared (IR) wavelengths. At longer (radio) wavelengths, in the millimetre range, the clouds are transparent to varying degrees, which allows astronomers to observe emission from molecules like carbon monoxide (CO). From observations of emission at a range of wavelengths the typical cloud has been characterised. The key characteristics of molecular clouds are summarised in Table 1 and discussed in following paragraphs.

Object	Size (pc)	Temperature (Kelvin)	Mass ($M_\odot$)	H_2 Density (cm^{-3})
GMC	20-50	20	10^5-10^6	100-300
GMC Cores	0.05-1	100-200	10-1000	10^7-10^9
Barnard Object	10	10	1000-2000	100-10000
Bok Globule	1	10	1-1000	$> 10^4$

Table 1: Molecular cloud typical characteristics. Figures from Ostlie and Carroll [3], and Kaufmann and Freedman [7].

Molecular cloud composition is primarily molecular hydrogen (H_2), approximately 99.99%. The clouds contain many other simple molecule types in gas phase. CO is the second most abundant interstellar molecule, but at least 120 are known [1, 2], with up to 13 atoms. Table 2 lists a sample of those found. Molecular clouds also contain grains of dust (solid phase) ranging in size from large molecules up to approximately 0.3 μm [8]. Silicate and carbonaceous materials are believed, from matching models to observations, to form the bulk of the dust grain material.

Diatomic	Triatomic	Larger
H_2	CO_2	CH_4
CO	H_2O	NH_3
OH	HCN	H_2CO
C_2	N_2O	$HC_{11}N$
NaCl	SiCN	

Table 2: Sample of molecules found in molecular clouds. Extract from Wootten [2]

The number density of the gas in molecular clouds varies between 10^3 and 10^6 cm^{-3} [1]. By way of contrast, the number density for ambient ISM gas is less than 1 cm^{-3}. At the temperatures typical for these clouds H_2 is largely inactive in radiation terms. Consequently, densities are derived from observations of more active tracer molecules such as CO, mainly at λ=2.6 mm, which gets much of its emitted energy from collisions with H_2 molecules. Other molecules that have been used as tracers are CH, OH, CS, and C_3H_2 [3]. Isotopic variants of these molecules, such as ^{13}CO and $C^{18}O$, can also be used. Emissions from each tracer are affected to differing levels by absorption within the cloud and can thus be used to probe of different portions of the cloud. Perturbations of trace emission lines by gas flows and rotation are also used to determine internal turbulence.

Bok globules and the extremely dense GMC cores are likely places for star formation based on the Jeans' criterion. Indeed, IR surveys of Bok globules indicate that most of these objects hide newly minted stars. A strong correlation between OB associations, young, hot stars with short lives, and GMCs indicates that star formation occurs in these regions also (During their short life OB stars cannot move far from their birthplace).

Despite the inconvenience to observational astronomers, dust plays a number of important roles within molecular clouds. In the densest regions dust concentrations are high enough to absorb the majority of incident UV radiation and re-radiate it in the IR range. This process protects hydrogen and other molecules from photo-dissociation and, because the clouds are largely transparent to IR, effectively keeps the cloud cool by radiating excess energy away. Dust is also thought to act as an intermediary to bring component atoms together to form the observed molecules. This mechanism is crucial to the formation of H_2 which would not normally bond into molecules under typical cloud conditions.

While not directly observable, magnetic fields, have an effect on charged particles that may be seen. The field may act to align electrically-charged dust grains resulting in preferential polarisation of reflected light that may be observed optically. In the outer reaches of clouds, where incident radiation frees electrons from their parent atoms, radio-frequency synchrotron radiation may betray the presence of magnetic fields. The presence of magnetic fields is largely irrelevant in predominantly neutral regions but, in regions with net charges, the field may provide a support against collapse by resisting gravitational motion of the ions.

Collapse

From a cold, dark cloud of molecular gas the path to a being a young star involves contraction of the gas. Typically, there needs to be 20 orders of magnitude increase in the central density of the collapsing cloud and 7 orders of magnitude decrease in size [9]. Precise triggers for collapse are not known, but possibilities include internal turbulence, external explosive events like supernovae, and the loss of magnetic support through migration of ionised atoms and molecules. Once collapse begins, matter close to the centre of collapse accelerates inward, away from the outer layers. This runaway collapse phenomenon, dubbed inside-out collapse, follows in general terms from the analysis done by Jeans, and was covered in detail by Shu [10]. While not the only theory, it is one of the most widely supported.

Early in the collapse of a dense core, thermal energy generated by the increasing density is easily radiated away because the cloud is still largely transparent to IR radiation. The cloud, therefore, is not buoyed by thermally generated pressures and can collapse unimpeded (free-fall) until the cloud becomes more opaque. When the central density climbs high enough to become opaque to IR wavelengths the cloud approaches thermal equilibrium, that is, thermal pressure nears balance with gravity and collapse is slowed. At this stage the object is quite warm, but far short of the temperatures and pressures required for fusion.

The, still free-falling, outer material continues to accumulate onto the the core with the added mass serving to compress and further heat the object. This is called the accretion phase, and the object is a protostar. Eventually the protostar accumulates sufficient mass for the core temperature and density to support deuterium fusion, the star core ignites briefly, and quickly exhausts this fuel. Stars in this phase are referred to as pre-main-sequence (PMS) stars. Further contraction and accretion is required to attain hydrogen fusion. After an initial settling-in period the new star starts an extended life on the main sequence.

During collapse, conservation of angular momentum dictates that any small rotation the original molecular cloud material had is amplified. The spin rate has increased and the material flattened into a disc. The protostellar (accretion) disc is observed, in remnant form, around exposed young stars.

Fragmentation and the Initial Mass Function

In the idealised situation studied by Jeans it's reasonable to expect an entire GMC core or globule to collapse into a single star of a mass much higher than those observed. However, these clouds are not spherical, density is not uniform within, and the gas is turbulent. Only the densest parts of the Bok globules or GMC cores are candidates for collapse, and these are scattered throughout the cloud. Consequently, collapse happens in many places and fragments the cloud. Not surprisingly, stars are quite likely to be born in groups within single clouds.

Fragmentation of the cloud collapse also serves to reduce the number of high-mass stars born. To arrive at a high mass star requires a large amount of raw material and a correspondingly large initial cloud. The larger the initial cloud, the more likely it is to have more than one slightly over-dense region, and therefore the more likely it is to collapse into several, smaller stars. The distribution of initial stellar masses is called the initial mass function (IMF). The IMF is a topic of ongoing research, but it does seem that the distribution follows a series power-law functions with differing coefficients applied to high and low mass ranges. Small stars are several orders of magnitude more numerous than large stars.

High mass stars, destined for classes O and B when they reach the main sequence, emit much of their radiation in the ultraviolet (UV) range. This radiation is sufficiently energetic to break the surrounding molecular hydrogen apart, ionise and heat the gas, creating an H II region. The strong solar winds associated with these stars also serve to clear the surrounding regions of material, effectively halting further formation in this area. Consequently, high-mass star clusters usually contain just a handful of members. H II regions are conspicuous, an easily seen example is the Orion Nebula, which houses several young, high-mass stars called the Trapezium cluster. Erosion of surrounding dark nebulae is also evident in Hubble Space telescope (HST) imagery of the Eagle Nebula.

Studying Young Stellar Objects

The earliest stages in the life of a YSO are shrouded in the cloud from which the YSO was calved, and obscured by material still in-falling from the accretion disc. The visible radiation from hot objects deep in the clouds is absorbed and scattered by the dust granules causing them to warm up and radiate. One practical means of probing this phase of a star's life is to examine the energy, the spectral energy distribution (SED), that is emitted by the surrounding dusty clouds. Typical SEDs are shown in Figure 2, and can be categorised into four classes:

- Class 0. Sub-millimetre and far-IR peaks, with a distribution similar to a blackbody curve, are characteristics of Class 0 objects. These portions of the spectrum are associated with cold dust, which leads to the conclusion that the objects are very deeply buried.

- Class I. The SED of Class I objects dominated by a rising energy at longer ($> 2\mu$m) wavelengths, and are broader in nature than a single temperature blackbody. This energy excess is believed to derive from the presence of substantial circumstellar discs.
- Class II. The SED for Class II objects peaks in the near-IR or visible range. They display an excess in the IR region, but not as marked as that displayed by Class I objects. These objects have been verified to be young stars with optically thick circumstellar discs.
- Class III. Having consumed or ejected their circumstellar material, Class III objects are the closest to main sequence stars. Their SED is close to that of a blackbody, peaking in the IR and visible, but their IR output tails off more sharply than a Class II object. If plotted on an HR chart they generally lie just above the main sequence. These objects provide valuable input to refine theoretical models of pre-main-sequence evolution.

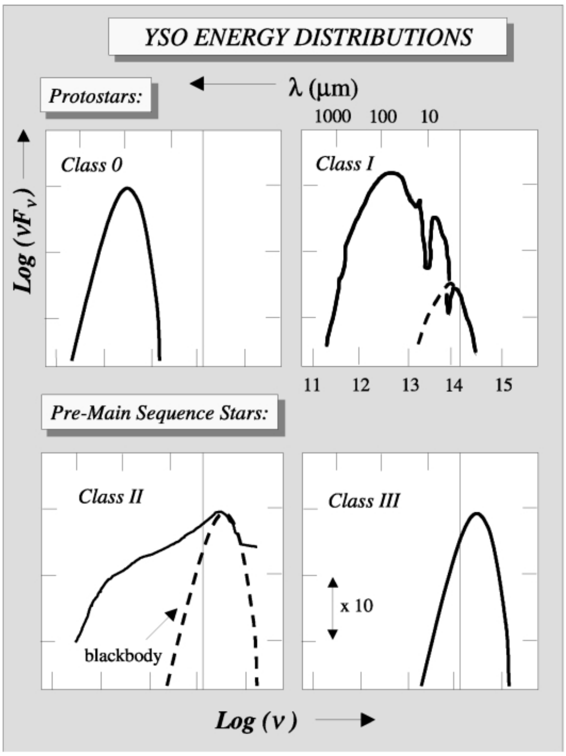

Figure 2: Classification of Young Stellar Objects. The vertical line indicates the red end of the visible spectrum. From Lada and Kylafis 1999 [11].

Characterisation by SED requires study of the radiation from visible through near IR (10 μm - 1 μm, NIR), mid-IR (50 μm - 10μm, MIR), far-IR (0.3 mm

- 50 μm, FIR), and sub-millimetre (1 mm - 0.3 mm) ranges. The FIR, MIR and portions of the NIR ranges can only be explored from outer space because the Earth's atmosphere is largely opaque to these signals. The HST carries the NICMOS instrument which covers the close end of the NIR (0.8 - 2.5 μm), while instruments like IRAS (1983) covered MIR and FIR (12, 25, 60 and 100 μm). The sub-millimetre range requires efficient, large telescopes and very sensitive receivers and remains largely unexplored as a result.

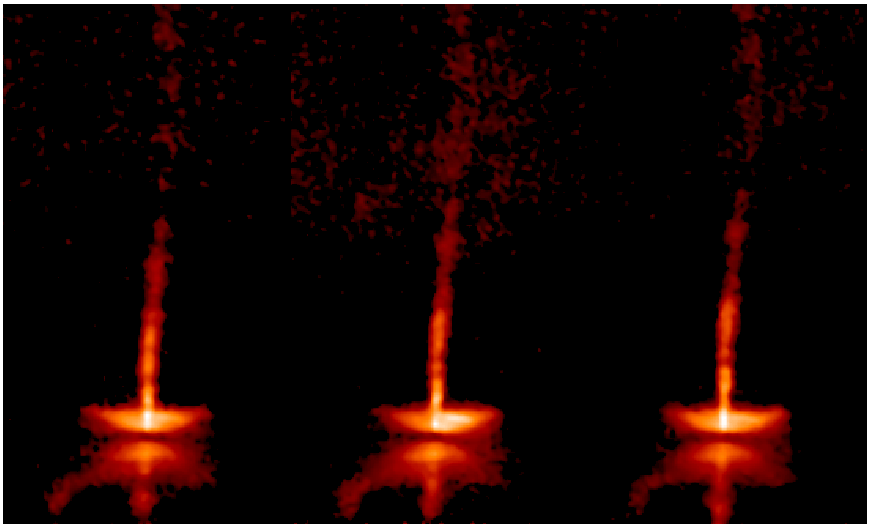

Figure 3: Time lapse images of Herbig-Haro object HH30 taken using HST over a six year period. Clearly visible are movements within the jet structures. The source star is obscured by a dusty torus that lies between the two disc shaped reflection nebulae. Credits: Alan Watson (Universidad Nacional Autonoma de Mexico, Mexico), Karl Stapelfeldt (NASA Jet Propulsion Laboratory), John Krist (Space Telescope Science Institute), and Chris Burrows (European Space Agency/ Space Telescope Science Institute)

The disc-like nature of the material around young stars has been directly observed by the HST. Figure 3 shows reflected light from the upper and lower surface of a dusty disc about the source star in HH30. The source star is not directly visible in this side-on image because of obscuring dust. Also visible are variations in the brightness of the disc material possibly caused by hot spots on the source star or density variation in the dust. Pre-main-sequence stars often produce bipolar outflows (jets) of material roughly perpendicular to the accretion disc. Jets are clearly visible in Figure 3. The material in these flows is moving at speeds in the order of several hundred kilometres per second. Collimation of the jets implies the presence of strong magnetic fields in the vicinity of the source object. The impact of this jet material on the surrounding gas and dust produces shock fronts resulting in clumps of hot, ionised gas. These clumps, called Herbig-Haro (HH) objects, are characterised by emission spectra in the visible range. The glowing clumps are seen to move, change size, shape, and brightness over time (weeks in some cases), clearly demonstrating the variability of the obscured source of the outflows. The spectra of HH objects betray the chemical makeup of the outflowing and cloud material.

Apart from observation, astronomers make use of increasing computer capability to run simulations of stellar formation processes. Adaptation of simulation models to match new observational evidence allows astronomers to piece together a more complete understanding of the process. Typical models cover areas like turbulence in clouds, magnetic fields, the effects of dust, collapse and accretion disc dynamics, and expected emissions. While these models are still far from perfect they are useful in determining what is possible, what to look for, and studying phenomena that simply cannot be measured with ease.

Limits of Knowledge

Despite decades of research and the high technology observational tools brought to bear on the sites of star formation there are still many unanswered questions. In addition, in areas astronomer's have general understanding there are many details of that are beyond our grasp.

The limits of our resolving power do not permit probing of the detailed structure in the immediate vicinity of YSOs. Projects like the ESO Very Large Telescope (VLT, `http://www.eso.org/projects/vlt/`) expect to be able to use optical interferometry to resolve objects about 0.3 AU across in the nearest star-birth regions. Angular resolution of observations at radio wavelengths can be improved using interferometry techniques and facilities like the NRAO Very Large Array or Very Long Baseline Array. Improved space-borne facilities, such as the HST Advanced Camera for Surveys and revitalised NICMOS, will allow better coverage of the visible and NIR ranges. With improved antenna and receiver systems, exploration of emission in the sub-millimetre realm will become more practical.

Some phenomena, such as bipolar outflows, the role of magnetic fields and turbulence in star-birth, and the behaviour of matter in accretion discs are only partially understood. The complete understanding of these requires further theoretical research, coupled with improved simulation and observation. Literature searches in these areas indicate large amounts of modelling research is already underway.

Conclusion

Astronomers have identified the location of stellar nurseries in molecular clouds of varying size. Using IR, radio, and optical observation the conditions in these clouds have been characterised. Young stellar objects have been studied through spectral energy distributions and through direct imaging. Astronomers have used a wide array of technology to make these observations.

The story of star formation, while understood in general terms, is far from being a closed book. Much research remains to be done on the various phenomena involved.

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