The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 2: Where Stars Come From

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http://kicp.uchicago.edu/~humensky/ComptonLectures.htm
October 11, 2008

Part 1. Some Stellar Basics

When we look up at the night sky, we see bright stars and dim star, red stars and blue stars. What drives these differences?

For brightness, there are two easy answers: how bright a star looks is a function of its distance from earth and its luminosity (plus a third answer – interstellar absorption – that we'll ignore for now). The brightness drops with distance by an amount proportional to the square of the distance because the light from the star is spreading over an area that grows with the square of the distance – this is known as the inverse-square law.

The luminosity of a star, its total radiated power output, is controlled by its temperature and size: hotter or larger stars have a higher luminosity than cooler or smaller stars.

The color of a star is also related to its temperature: just as with flames on earth, red stars are cooler than blue stars. This is because the spectrum of radiation from a star peaks at a particular wavelength characteristic of its temperature. A hotter star will peak towards shorter wavelengths, in the blue or UV range, and thus emit more blue light than red, causing it to look bluer to us.

What sets a star's temperature and luminosity? They are set by its mass and its evolutionary stage. For "main-sequence" stars, stars burning hydrogen in their cores, their temperature and luminosity are set almost exclusively by their mass and age. More massive stars require a higher core pressure to stave off gravity, and this in turn creates a higher temperature and a larger radius, and both of those force the luminosity to rise quite dramatically with mass.

A star's mass also determines its lifetime: higher-mass stars burn through their fuel far faster than low-mass stars. For example, the Sun is 4.56 billion years old and expected to have a main-sequence lifetime of about 12 billion years. A star with only half the mass of the sun, however, has 3 % of the luminosity and a lifetime of ~700 billion years, far long than the age of the universe. In constrast, a 25-solar-mass star has 80,000 times the luminosity of the Sun and a lifetime of only 4 million years!

In order to understand the relationships between mass, temperature (color), luminosity, and evolutionary stage for a population of stars, astronomers use a “Hertzsprung-Russell” (HR) diagram. Figure 1 is an example of an HR diagram. On its X-axis, it gives the spectral class of the star across the top. The spectral class indicates the color of a star, with O and B stars being blue and M stars red. On its Y-axis, it gives the visual magnitude of a star on the left. The magnitude is a measure of a star’s luminosity on a logarithmic scale. Any given star will appear as a point on an HR diagram, and the black points and circles indicate show where some prominent stars appear. Often the axes will show the temperature and luminosity rather than spectral class and magnitude.

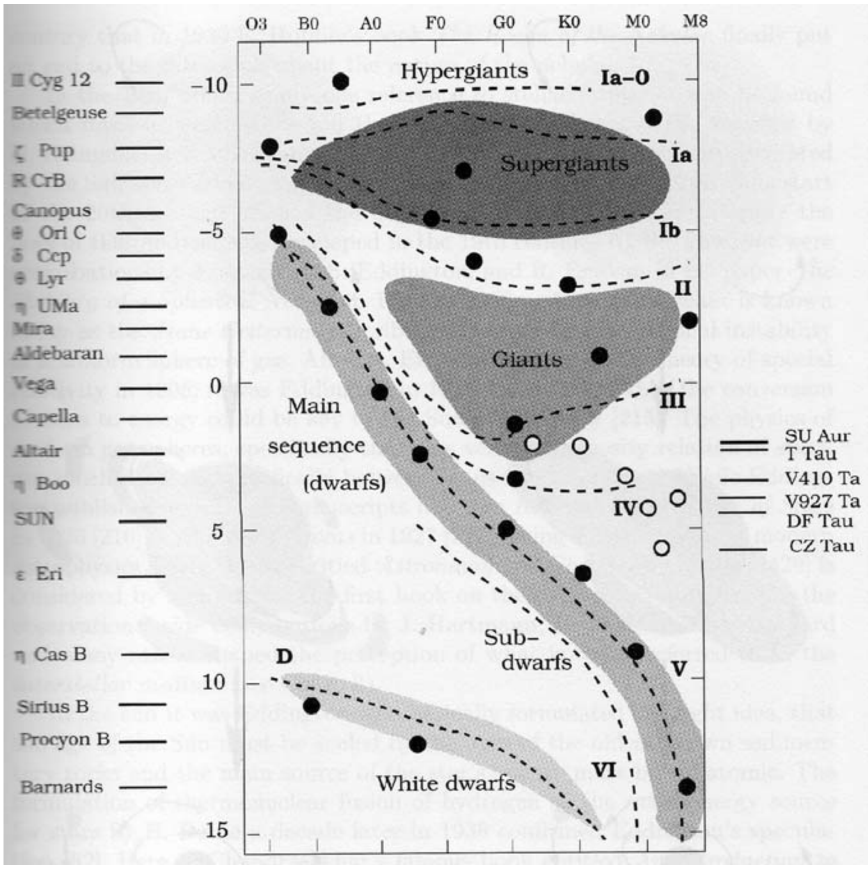

Figure 1. Schematic example of a Hertzsprung-Russell diagram, showing the relationship between a star’s luminosity (Y-axis, using the visual magnitude scale) and its temperature or color (X-axis, using the spectral class scale).

The first feature to notice in the HR diagram is how the stars form a stripe that goes from the lower-right towards the upper-left: this is known as the “main sequence.” It is NOT a sequence in the sense of a star starting at one end and progressing towards the other as it evolves! Instead, the main-sequence stars are the ones that are burning hydrogen in their cores; for them, their temperature and luminosity – and hence their place along the main sequence – is set simply by their mass, with more massive stars (10-100 solar masses) towards the upper-left and less massive stars (as low as 0.08 solar masses) towards the lower-right. The main sequence is where stars spend most of their lifetime. For example, the sun spent about 20 million years forming as a “protostar” before reaching the main sequence; it will spend about 10 billion years on the main sequence before evolving into a red giant.

Later stages of stellar evolution lead to the burning of helium and other heavier elements, and it is during these stages that stars can evolve into giants and supergiants, the denizens of the upper-right (cool but luminous) region of the HR diagram. Ultimately, low-mass stars end as white dwarfs (hot but dim), before slowly fading away.

Part 2. Giant Molecular Clouds as Stellar Nurseries

Giant Molecular Clouds (GMCs) are amongst the most massive objects in the galaxy, with masses of $10^4 – 10^6\ M_\odot$. They are not necessarily gravitationally bound and, like all clouds in the galaxy, are transient structures with lifetimes on the scale of 10’s of millions of years. Their lifetimes are linked to the time scales of stellar formation, which seems natural since the formation of massive stars can produce ionizing radiation, winds, and supernovae that are all capable of expelling or destroying molecular material. GMCs are frequently the sites of star formation, though smaller clouds are also capable of forming stars. Star formation in any size of cloud requires that cold, dense regions develop – the initial formation of these regions can be triggered by turbulence and motion generated in the rotation of the galactic spiral arms, or by more local events like compression of gas by a nearby supernova remnant or the collision of two clouds.

Figure 2 shows a schematic view of a Giant Molecular Cloud, and how it can evolve while stars are forming within it. The cloud typically begins (Fig. 2A) enveloped by a surrounding layer of atomic hydrogen – this atomic hydrogen provides shielding from the destructive power of the interstellar radiation field. The GMC itself is made up of dust and molecules, with H_2 being the dominant component. It may be on the order of ~300 light years across, with an average density of ~1000 cm^{-3} and a temperature of 10-50 K. Scattered throughout the GMC we find dense clumps and cores of matter. The cores are small structures, ~0.3 light years across, that are likely to form single stars or binaries. The clumps are larger structures, ~30 light years across, and if gravitationally bound are the progenitors of clusters of stars.

As the clumps and cores begin to contract into stars, the most massive ones will rapidly progress to the main sequence and begin burning as hot stars of types O and B. This can happen in as little as $10^4 – 10^5$ years for the most massive stars ($\gtrsim 10\ M_\odot$), but takes 10 million years or longer for solar-mass stars. Thus, the low-mass stars are still a long time from beginning to burn when the earliest generations of high-mass stars are blazing away! Figure 2B shows what can happen to the cloud once (if) massive stars start to burn: because of their high temperature, they shine brightly in the UV, and UV photons are energetic enough to break apart molecules and ionize the remaining neutral hydrogen and evaporate the material of the molecular cloud. The Eagle Nebula, discussed below in Part 4, shows an example of this activity.

The resulting situation is that the region surrounding the massive star is no longer a molecular cloud but rather warm ionized hydrogen, with some dense cores still surviving. As the GMC continues to age and evolve, additional stars form and the ionized region grows. In Figure 2C, we see a late stage: most of the region has been ionized, except for some small patches that were dense and/or far enough from the massive stars to survive. A number of stars have formed or are still forming, and a number of dense cores remain. Some of these cores will develop comet-like tails in response to the stellar winds and ionizing radiation hitting them.

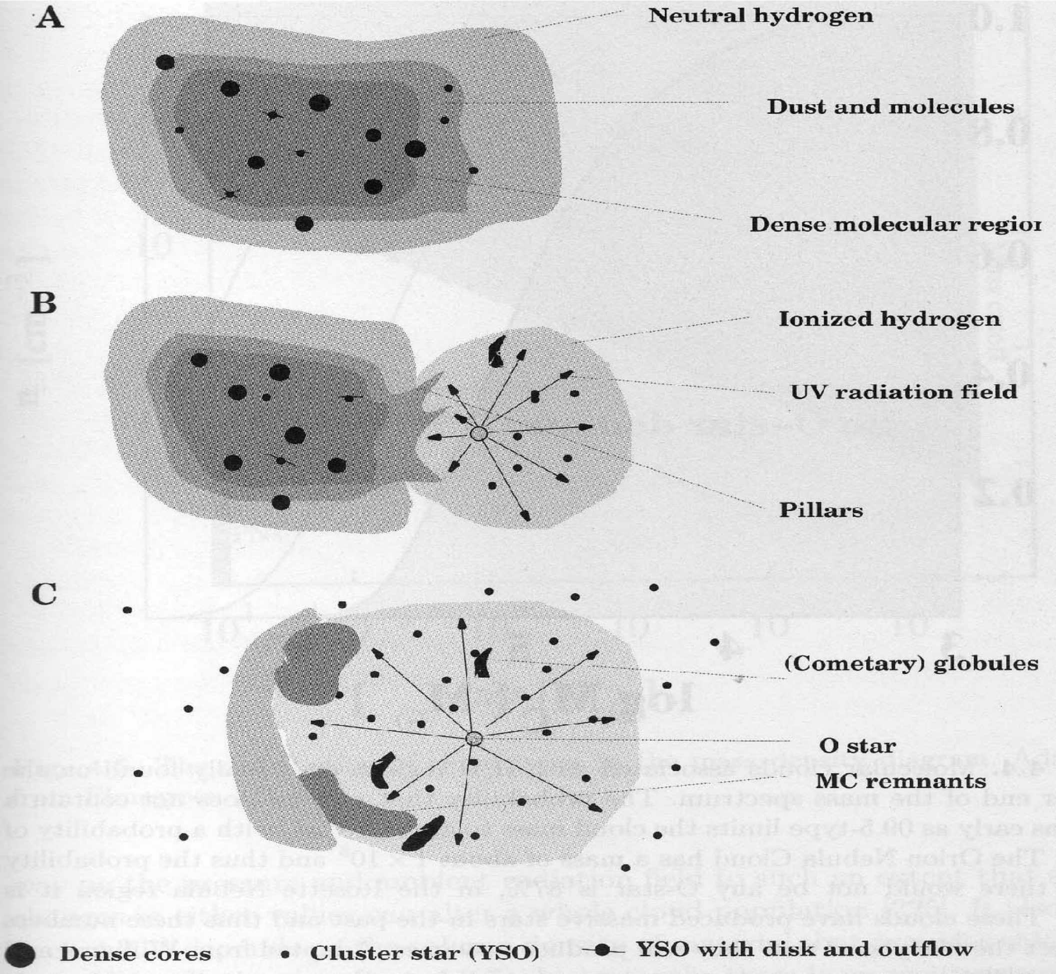

Figure 2. Evolution of a Giant Molecular Cloud into a star-forming region.

Part 3. Collapsing the Gas into a Star

The formation of stars requires a delicate dance between a number of forces: gravitational attraction, thermal pressure, and radiative cooling. In recent decades, the importance of other forces like turbulence, rotation, and magnetic fields has also come to be appreciated and explored. Astronomers are still working out the roles each of these forces plays.

For a cloud of gas to begin contracting on its own under the force of gravity, it needs to be relatively dense (on the scale of the interstellar medium) and it needs to have a low pressure. Since pressure is related to temperature, this means the cloud needs to be cold, and typically it is clouds with temperatures that are initially ~ 10-50 K that host star formation.

As a cloud of gas contracts, the matter falling towards the center heats up. If there were no mechanism for dissipating this thermal energy, the pressure would rise and stop the protostar's contraction. However, the presence of molecules and dust particles provide an efficient cooling mechanism: they convert the kinetic energy of the infalling matter into infrared light. The IR emission is able to radiate freely out of the cloud, dissipating the energy, cooling the cloud, and allowing contraction to continue. This process of converting gravitational energy into thermal energy and radiation is known as Kelvin-Helmholtz contraction, after the two 19th-century physicists who proposed the idea as a mechanism for powering the Sun.

After a few thousand years of gravitational contraction, a solar-mass protostar's surface will reach temperatures of 2000 – 3000 K. Since it is still much larger than the final star, its surface can radiate an immense amount of energy, and the protostar's luminosity can be 100 times the Sun's! Yet the protostar is still hidden within the dense nebula out of which it is forming, and cannot be seen in the optical – IR telescopes are required to study these objects.

This gravitational contraction continues until the core of the star heat to a few million kelvins (K), at which point fusion of hydrogen into helium can begin. The energy released by fusion reactions stabilizes the interior of the star against gravity, and a main-sequence star is born.

What is the range of masses that a zero-age main-sequence star can have? At the low end, stars need to be massive enough for the pressure and temperature in the core to be high enough to enable hydrogen fusion, and the minimum mass for this is about 0.08 $M_{\odot}$. Protostars below this mass never begin nuclear fusion, and continue to glow faintly via Kelvin-Helmholtz contraction as "brown dwarfs." At the other end of the scale, the most massive protostars (approaching 200 $M_{\odot}$) heat so rapidly while contracting that radiative cooling can't keep pace; they develop such high internal pressures that they overcome gravity and blow off their outer layers, disrupting the protostar. Thus, main-sequence stars have masses in the range 0.08 – 200 $M_{\odot}$. The number of stars of a given mass drops rapidly as the mass increases, however, making the most massive stars quite rare.

Out of a single Giant Molecular Cloud, a number of star clusters might form over a period of some tens of millions of years. Eventually, most of the remaining molecular gas has been either ionized or expelled from the region, and star formation ceases. Star clusters may have 10's, 100's, or up to several thousand stars. Similar mechanisms for star formation appear to operate in smaller clouds as well, and while the majority of stars in the galaxy form in clusters, a small fraction can form as isolated stars – a cluster of one.

Part 4. The Eagle Nebula, An Active Site of Star Formation

The Eagle Nebula, about 6,000 light-years away, is a splendid example of star formation in the midst of a massive molecular cloud, and the resulting impact of those stars on the cloud. Figure 3 shows the Eagle Nebula on the left, and a close-up of its famous Elephant Trunks on the right.

In the central region of the Eagle Nebula, the star cluster NGC 6611 has carved out a large cavity of ionized gas. This star cluster contains stars with masses 2 – 85 $M_\odot$ and ages of 2 – 3 million years – a very young cluster! It is the UV radiation from the massive stars in this cluster that has ionized the central region of the nebula. In the last few years, a large number of pre-main-sequence stars has also been identified in the cluster.

The Elephant Trunks themselves (numbered I-V in Figure 3 (left), and in a close-up view of I-III in Figure 3 (right)) are fingers of gas and dust that have so far survived the ionizing radiation of the star cluster while the cloud material around them has been evaporated. The columns of these fingers are relatively low in density; they survive because the caps of the fingers are made of dense molecular cores that shield the rest of the finger.

The fingers have complex structures, including numerous dense clumps of gas and dust that are referred to as Evaporating Gaseous Globules (EGGs). Some of these seem to have young stellar objects embedded within them, a sign of ongoing star formation in the nebula. Because of their high density, many of them are opaque even in the IR and it is unclear how many of the EGGs host young stellar objects. Researchers are also still unsure whether the star formation is actually being *triggered* by the ionization front from the nearby star cluster, or whether it was ongoing and is just being *revealed* as the ionization front removes the dense material that is blocking our view. We still have a lot to learn about the mechanisms that drive star formation and about the feedback of massive stars on their environment, and regions like the Eagle Nebula are proving to be fertile grounds for study.

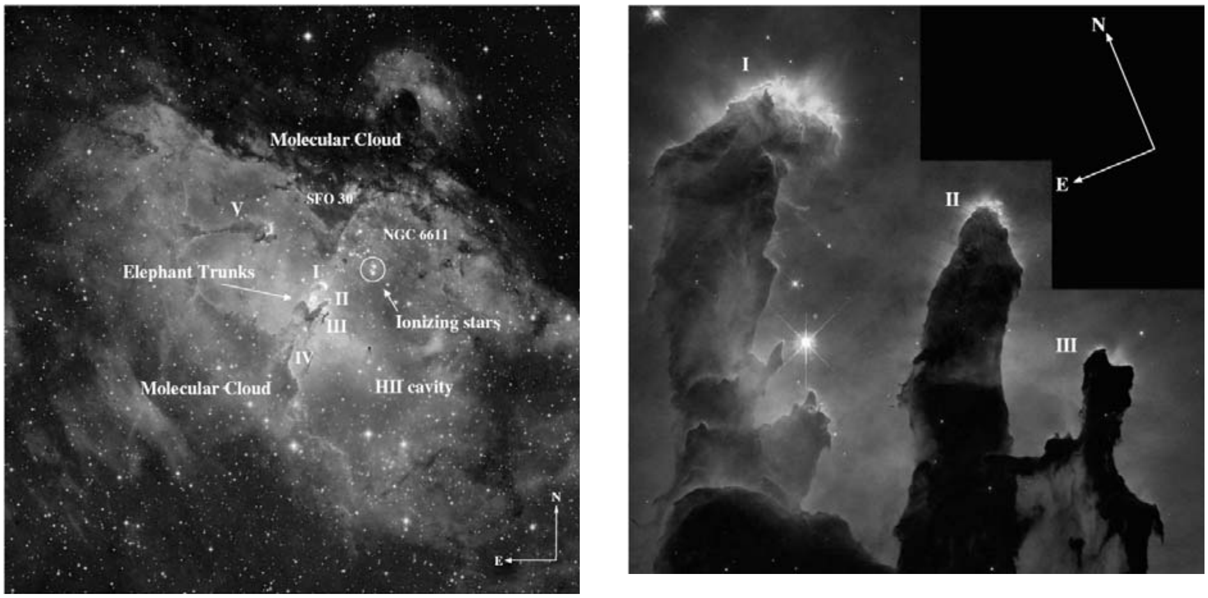

Figure 3. (left) The Eagle Nebula, a site of recent and ongoing star formation. (right) Close-up of the Elephant Trunks, structures within the Eagle Nebula formed by photo-evaporation of the molecular cloud by ionizing radiation from nearby massive stars.

Coming Up In Two Weeks: Stellar Evolution and Demise

Reminder! No lecture next Saturday, Oct 18th. We resume again in two weeks (Oct 25th), when we take a quick look at how stars evolve and then examine how they die, as solitary white dwarfs and in novae and supernovae.

References

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Oliveira, J. M. A chapter in the Handbook of Star Forming Regions, Vol. II, ed Bo Reipurth. arXiv: 0809.3735.

Salaris, M. and Cassisi, S. Evolution of Stars and Stellar Populations (2005)

Schulz, N. S. From Dust to Stars: Studies of the Formation and Early Evolution of Stars (2005)

Credits for Figures

Figure 1: Reproduction of Figure 2.5 from N. S. Schulz's book.

Figure 2: Reproduction of Figure 4.3 from N. S. Schulz's book.

Figure 3: Reproduction of Figures 1 and 2 from J. M. Oliveira's article.