Interstellar Molecules

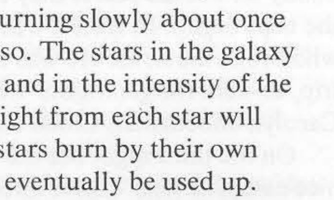
by Gillian Knapp

When you look into the sky at night, you see our galaxy as a band of light crossed by dark patches. New stars are born in dark patches like these, which are not holes in the galaxy but huge clouds of gas and dust that block out the starlight behind them.

Our galaxy contains about 100 billion stars arranged like a flat wheel turning slowly about once every 100 million years or so. The stars in the galaxy vary greatly in size, in age, and in the intensity of the light they give off, but the light from each star will eventually go out because stars burn by their own internal energy, which will eventually be used up.

If you could look at the galaxy from the top, you would see that the surface is not smooth but irregular, with the light emitted from great arms in a spiral pattern. These arms are the places where both the gas and new stars are the densest, because it is out of the clouds of gas and dust that new stars are born.

The universe consists mostly of the gas hydrogen. We think, in fact, that when the universe first formed, it contained only two elements, hydrogen and helium. We also know that the dark patches out of which the stars are born are made of dust grains that contain atoms much heavier than hydrogen and helium, and we think those atoms were produced during the deaths of stars.



A schematic cross-section of a typical star shows the balance between the force of gravity and the radiation pressure within the star, plus a second kind of balance—that between the production of energy in the core and the loss of energy from the surface.

A star is a large spherical cloud of gas maintaining itself in a two-way equilibrium. It's in balance between the inward force of gravity, which tends to try to pull it together and contract it into a point, and the outward pressure of radiation produced in its center by the nuclear reactions that turn one element into another—nuclear fusion. In the case of a star like the Sun, the fusion is of hydrogen atoms into helium atoms. In some other stars helium atoms fuse into carbon atoms. That's the first kind of balance—the balance that keeps the star the size it is.

There's also a second kind of balance. The star is shining, and energy is radiated from its surface which must be in continuous balance with the energy produced in its heart. Therefore, the star is continuously losing energy, and so it can't last forever. The length of time it will last has an inverse dependence on its size. The bigger the star, the faster it will use up its energy.

When the star has lost all the energy it can produce in its center and is no longer radiating energy, gravity takes over and starts to crush the center of the star. If the star is massive enough, the pressure gets very high in the center and more and more complex reactions take place. Eventually the reactions go so fast that the process simply runs away, and the star blows away its outer envelope.

In the smallest stars, the nuclear reactions are fairly slow, and the explosion that blows off the outside envelope is not a very violent one. The explosion in the center of a somewhat more massive star is more violent and more material is blown out. The most violent stellar explosion of all is called a supernova. In such an explosion, a single star can suddenly become brighter than a whole galaxy. As time passes, the gas blown away from the exploding star gradually diffuses through space.

This expanding material does not contain just the hydrogen and helium that made up the star originally. It also contains heavier, more complicated atomic nuclei produced in the nuclear reactions in the center of the star, and in particular that were produced in the runaway nuclear reactions that immediately preceded the final explosion. Among the materials thrown out into the galaxy by the explosion of a large star are atoms of carbon, oxygen, sulfur, calcium, nitrogen, uranium—all of the atoms heavier than hydrogen and helium. These atoms fly out into space and gradually enrich—or contaminate—the hydrogen or helium gas that is already there. So the dust clouds from which stars are born depend on the deaths of an earlier generation of stars, and all the heavy elements of which this earth and its inhabitants are made were produced in such cataclysmic explosions earlier in the life of the galaxy.

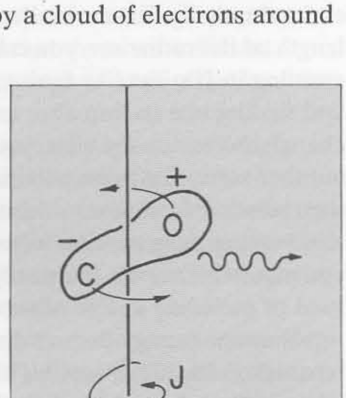
We know that the very hot stars we observe are new because the hotter a star is the quicker it radiates its energy. Such hot stars can live only a few million years or so, so we know that they have to have been formed fairly recently (in a cosmic sense). Some of these stars are surrounded by clouds of dust, which scatters the light from the star in the same way that cigarette smoke scatters light and so looks bluish and hazy. Some stars are surrounded by gas whose characteristic red glow shows that the gas is hydrogen heated by the hot star to a very high temperature—about 10,000 degrees Centigrade. So, when we see those newborn stars surrounded by gas and dust, it seems very likely that they must have formed out of a cloud of gas. This is circumstantial evidence that stars are formed in the large dust clouds.

How does it happen? By the time we see a large region of glowing gas surrounding a star, it is obviously too late to watch the birth happen, because the star is already formed. What goes on in a dark cloud that causes the stars to form? Until recently it was impossible to answer this question for the very simple reason that you can't see through the dark clouds. The dust in them completely stops starlight from passing through.

Recently, however, two new avenues of astronomical research have opened up. We have been able to observe infrared radiation and radio-frequency radiation from interstellar molecules. Both of these forms of radiation can pass completely through dust clouds because their wavelengths are much larger than the dust grains themselves. The dust clouds contain a large variety of molecules in gaseous form, and by studying their radiation we can determine what is going on inside the dark clouds and hope to build a sort of scenario of the processes that lead to the formation of stars.

These great dark clouds are very large indeed. They contain from about a thousand to a million times as much material as our own Sun, which weighs a billion billion billion tons. The clouds are also very extensive—perhaps two or three light years in diameter—and of extremely low density. The number of molecules of oxygen and nitrogen and so on in a cubic inch of air at sea level on the surface of the earth is about 100 billion billion. Inside that same volume in these dark clouds out in space, the number of molecules and atoms is only about 10,000. So, although astronomers often call these objects "dense"—because they are much denser than the rest of the gas in the galaxy—they are nevertheless a much better vacuum than anything we can get on the surface of the earth. They are tremendously rarefied, but because they are so enormous there's a huge amount of material in them.

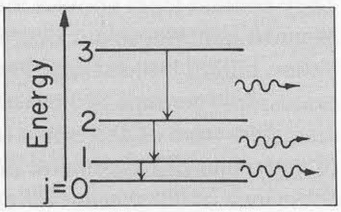
What do observations of interstellar molecules tell us, and how can we use that information to find out what is going on in the cloud? A typical interstellar molecule, one of the most abundant, is carbon monoxide, which consists of an atom of carbon and one of oxygen, bonded together by a cloud of electrons around



The CO molecule can rotate at various energy levels—that is, with various values of angular momentum (J). A decrease in J (a loss of energy) results in radiation.

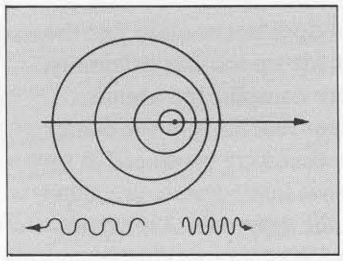
them. Because the carbon atom is different from the oxygen atom, the electrons are distributed asymmetrically; that is, there are more electrons on one side of the molecule than on the other. So it just acts like a small magnet, with the plus charge on one side and the negative charge on the other. Such a molecule, by rotating like a dumbbell, can interact with the electromagnetic field and cause radiation that we see as light or as radio or infrared waves, depending on the energy and wavelength of the radiation.

The molecules rotate, but things that small are allowed to rotate only at specific speeds (their rotation is quantized), and that means only with specific energies. This is rather like saying, if you're going up or down some steps, that you can stand on one step and then the next, but there isn't any place to stand in between. There is a specific gap between one step and the next. The energy of rotation of the molecules follows these steps, and the molecules' rotation can step up and down and lose a very specific amount of energy—depending on what the molecule itself is like and how fast it is rotating. A molecule that has two heavier atoms will rotate more slowly for a given amount of energy than one with two lighter atoms, for instance. Since each molecule rotates with characteristic speed and drops down these characteristic steps, each time it does so out comes radiation of a particular wavelength emitted only by this molecule. By measuring the wavelength of the radiation, you can tell which molecule is emitting it. It's just like tuning through a radio band and finding one station after another. Each time you change the frequency a bit, you hear the radiation from another station. At one particular frequency you "hear" the radiation from one molecule; change the frequency and you get the radiation from another molecule. So you can tell from the frequency of the radiation what kind of molecule you're observing.

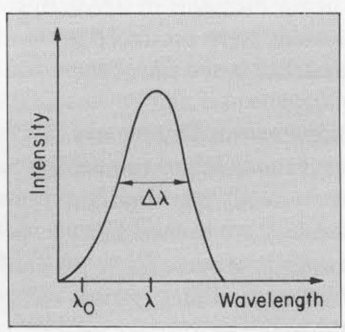


The transition from one value of J to another has a specific energy difference, depending on what the molecule is like and how fast it is rotating. Some of the transitions in the rotational energy levels of CO are shown above.

Now the energy doesn't come in at a very sharp frequency. Ideally, it would, but in space—as everywhere—the molecules inside the clouds are moving around because of the internal heat of the clouds. The clouds, in addition, might be rotating as a whole, as well as expanding or collapsing. The radiation from any object that is moving is changed slightly in wavelength. Waves in the direction of motion of a moving molecule get squeezed together, and so the wavelength gets shorter. If the molecule is moving away, the waves get spread out, and the wavelength is longer. From that small shift in the wavelengths at which the molecules radiate, you can tell at what speed the molecule is going. Since you have enormous numbers of molecules in the cloud and they're all rushing around at their own individual speeds, the radiation from the cloud will not occur at a sharp wavelength, but will be spread out over a small range of wavelengths.



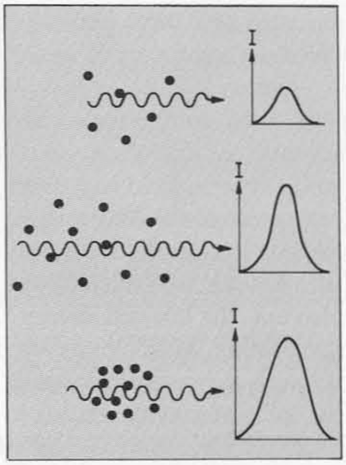
The radiation from a moving object shows the Doppler shift. It appears to have a slightly shorter wavelength if the motion of the object is toward the observer (right) and a longer wavelength if the motion is away from the observer (left).



The resulting emission can be expressed as intensity versus wavelength. The shift in wavelength (λ_0 to λ) measures the speed of approach or recession of the cloud. The wavelength spread ($\Delta\lambda$) measures the internal motions of the cloud.

From this you can tell two things about the cloud of gas that is emitting the radiation. First, if the emission is at a wavelength a little different from the proper central wavelength, you can tell that the cloud as a whole is moving away from or toward you at a certain speed. Second, the emission doesn't occur at a sharp wavelength, but at a spread of wavelengths, so you can measure the internal motions in that cloud. If the cloud is collapsing, for example, you can tell how fast from the spread of the radiation. If it is falling together very fast, the radiation is spread over a wide range in wavelength.

If there are a lot of atoms in a cloud, but the density is low, then the radiation from them simply



The intensity (I) of the emission of radiation from a cloud measures the total number of molecules in the cloud. The smaller the number of molecules, the weaker the signal (top). You cannot tell whether those molecules are in a low-density gas that is spread out (center) or in a high-density, very condensed gas cloud (bottom).

adds up. If there are only a small number of molecules, you observe only a weak signal. If there are more molecules, you observe a stronger signal. You can't tell whether the molecules are in a low-density gas that is spread out or whether they are in a high-density, very condensed gas cloud. You can only measure the total number of molecules. On the other hand, the gas can be so dense that, as one molecule radiates, the molecules in front of it absorb the radiation. In that case, all you ever see is the front face of the cloud, so a few molecules produce the same intensity as a lot of molecules, and all you can tell is the surface temperature of the cloud. If the cloud is at a higher temperature, the intensity of the radiation from the molecules at the front is higher.

We can, then, get all this information out of observations of molecules in a gas cloud in space: We can tell what molecules are present and how many there are of each; we can tell what the temperature of the cloud is, and we can measure the total density of the cloud. By making these observations at various points in a cloud, we can study the variations in temperature and density across the cloud. Finally, we can study the velocity field in the cloud—how fast its various parts are moving. Because the radiation is not absorbed by dust, we can see right into the cloud.

It happens that most of the interstellar molecules that we have studied to date radiate at wavelengths that vary between a few centimeters and about a millimeter or so. Caltech is fortunate in having a beautiful new radio telescope built by Robert Leighton at the Owens Valley Radio Observatory (see page 22). The telescope consists of a movable mount that holds a very large mirror, just like the mirror of an optical telescope. The diameter of the telescope is ten meters, and it is made out of hexagonal plates. The big mirror collects radio radiation, which is reflected up to a second, smaller mirror, and is then reflected back into a housing that contains receiving equipment operating at the appropriate frequency. This equipment receives the radiation and amplifies it; then the signal goes into a control room, where it is analyzed and recorded.

The wavelengths at which interstellar molecules radiate are usually very short, and the telescope surface has to be accurate to much better than the wavelength of the radiation that falls on it. Otherwise, it's like ground glass. You can't see a clear image through a piece of ground glass because the surface of it is rough, and the light waves are scattered as they pass through. The wavelength of the radio waves from some interstellar molecules is about a millimeter, so the surface of the telescope that is observing them needs to be accurate to much better than a millimeter all over. That means that the shape of the telescope, which is ideally a parabola, must not deviate by more than a tenth of a millimeter all over—either in total shape or in terms of local irregularities in the surface. The new telescope at Owens Valley has been machined to be accurate to much better than this tolerance and is, in fact, by far the most accurate in the world.

A very large number of interstellar molecules have been discovered—over 40 species. They are made up of common atoms—hydrogen, oxygen, carbon, nitrogen, and sulfur—combined into molecules like formaldehyde, various kinds of alcohols, water, and carbon monoxide. On earth, because the density of the atmosphere is so great, the natural state of hydrogen, or oxygen or nitrogen, is the molecular, but this is not necessarily true out in space. The density of materials there is so low that most of it is in single atomic form. It is only when the gas condenses and collapses together into a dense cloud that there are sufficient numbers of atoms close enough to each other for these molecules to form.

Furthermore, out in space there's a lot of high-energy starlight that easily destroys molecules by simply breaking their bonds open. It is only inside these dense dark clouds that molecules can get together and be protected by the dust from light from the nearby stars—thus allowing the molecules to persist.

In such clouds most of the hydrogen is in the form of hydrogen molecules. It's a particularly unfortunate property of the hydrogen molecule, however, that it doesn't emit any radiation via rotational transitions. This is because both atoms of the hydrogen molecule are the same, and therefore the cloud of electrons around them is evenly distributed, so that we can't study hydrogen molecules by these techniques.

The most common molecule that we can study is carbon monoxide. Another molecule that has been seen in a couple of clouds in space is ethyl alcohol, and it can be used to illustrate the enormity of those dark clouds and of the space in which they are found. The total amount of alcohol in those clouds—if distilled down into bottles—would amount to ten billion billion billion fifths of alcohol at 100 degrees proof. By comparison, the cloud from which our Sun formed contained 100 billion billion fifths of alcohol.

Of course, getting your hands on that alcohol wouldn't be easy. The densities are so low in space that there is only about one molecule of alcohol every cubic meter or so. This means that if the star ship *Enterprise* had a scoop out in front of it with a surface area of one square mile and was sweeping through such a cloud at the speed of light, it would take it a million years to gather enough alcohol for one drink.

The heaviest molecule observed to date is HC_9N, which consists of a long string of carbon atoms with an H on one end and an N on the other. It appears that carbon atoms like to form these long chains. The water molecule is one of the commonest molecules found in space. To date no truly life-forming molecules have been observed, such as amino acids or glycine, nor have any ring molecules been found. We have searched for some of them, and they don't appear to be there, but the frequencies of some of the others have not been measured well enough for us to look for them.

Of interest to earthbound chemists is the fact that molecules like N_2H^+ and HCO^+, which are singly ionized—a very difficult thing to have happen on earth —exist in abundance in space. On earth, densities are so high that while certain simple molecules can form, they immediately combine into more complicated molecules. So some molecules simply can't persist long enough on earth to be studied, but they can persist a long time in space because the densities are so low.

We can also make a study of molecules that contain isotopes. The common carbon monoxide molecule, for example, consists of $^{12}C^{16}O$, but you can also observe radiation from $^{13}C^{16}O$. Comparing relative abundances of these isotopes in space with those that you see on earth, we find that the material out in space has been enriched with more heavy elements and more isotopes through the process of stellar evolution.

Observations of a great many molecular spectral lines, then, lead to the construction of the following scenario for the formation of stars: A cloud of dust and gas in space is held together by the force of gravity, each molecule pulling on every other molecule and holding the cloud together. It will not automatically shrink down to a small object, however, because it is also hot; the internal energy keeps the cloud from contracting. Most clouds are pretty well in balance between the outward force of their internal energy and the force of gravity tending to pull them together. In order for stars to form, something has to happen to disturb that equilibrium.

To begin with, perhaps there is a cloud of interstellar gas of such low density that the material in it is mostly in the form of atoms. Then something comes along and gives it an extra squeeze. Such pressure could come from several things that we know about in space. One is the shock waves from the tremendous explosions that take place when stars die. So the death of one star may actually start the processes that result in the birth of other stars.

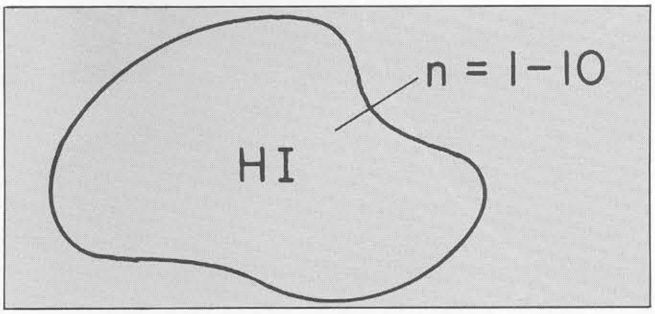
Another possible way for these high pressures to occur in our galaxy is from the non-even distribution of material. The density is higher in the spiral arms of galaxies than it is outside the arms. So if a cloud drifts into such a region, the pressure would be higher and it might get compressed.

However it happens, as the cloud gets compressed, its density increases, and the material in it starts to form into simple molecules like hydrogen and carbon monoxide. These molecules can radiate energy because they are heated up by collisions with other atoms in the cloud. Thus the cloud loses energy, its temperature drops, and it collapses. When smaller pieces of it are collapsed to much higher densities, the radiation of molecules such as hydrogen cyanide, formaldehyde, and so on can be detected. Then a little piece of this higher density material, pretty well in spherical shape, starts to get extremely hot in the center. Eventually it becomes so hot and dense that nuclear reactions can start. Out pours the radiation, which then balances the force of gravity, and a star is formed.

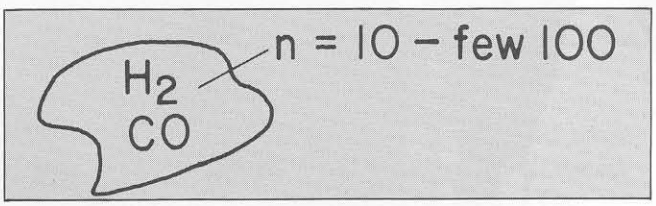
The final stage in this story of the birth of a star is that if the star is very hot and energetic, it will blow away the dark cloud of gas and dust remaining around it.

In summary, we have believed for a long time that new stars were contiuously being born in the dark clouds in our galaxy, but we didn't know how it was happening because we couldn't see into the depths of these clouds. This has been changed with the opening up of new regions of the electromagnetic spectrum in the short radio wavelengths and the infrared wavelengths. In the frequencies and intensities of those waves we can see the gradual increases in density and the gradual collapsing of material in the processes that precede the formation of a star.

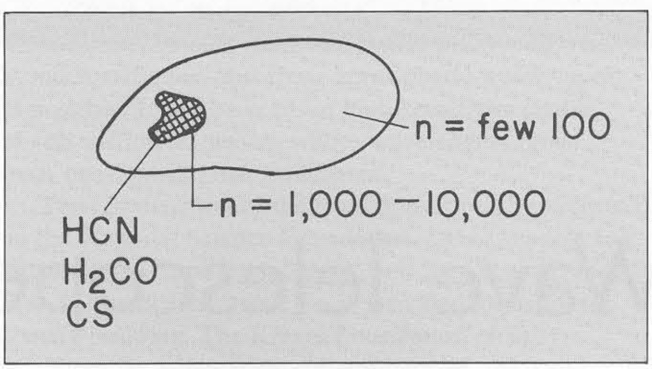
These regions are studied in the radiation of some fairly exotic molecules, which are very interesting in their own right from the chemical point of view. Among other things, they illustrate the ease of forming complicated molecules containing carbon, and show us that the materials of the dark cloud out of which our Sun formed contained a lot of heavy elements, and also contained complex molecules (most of which would be destroyed as the Sun was born). So the seeds for forming complicated organic molecules were already there in the dark cloud. Such molecules formed not only in our solar system, of course, but must do so in the gas from which other planetary systems were born. Perhaps such molecules contain the seeds of life everywhere in the universe. □



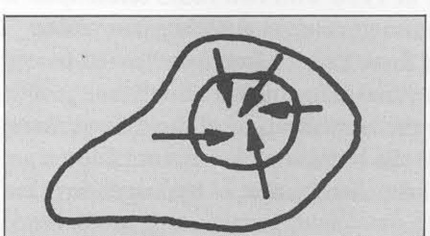
1. The formation of a star begins when a cloud of dust and gas in space starts to collapse. At that point the density (n) of atoms within the cloud is not more than about ten per cubic centimeter.



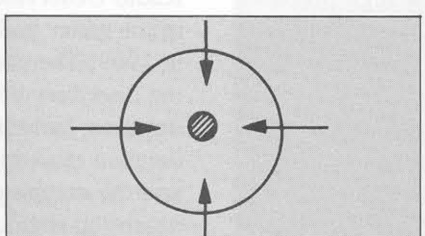
2. As the cloud collapses, the density of atoms becomes a few hundred per cubic centimeter, and simple molecules like H_2 and CO are formed.



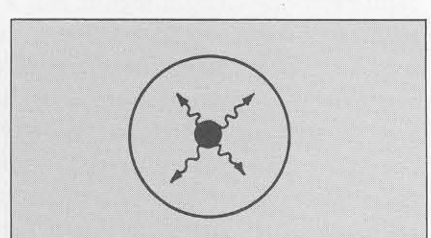
3. Eventually regions of up to 10,000 atoms and molecules per cubic centimeter begin to appear here and there in the low-density cloud. These higher density regions can be detected via their emissions from molecules such as HCN, H_2CO, and CS.



4. Some of the higher density regions contract into small spheres, becoming "protostars."



5. Because of gravitational collapse, the center of such a protostar heats up, becoming more dense.



6. When the center becomes hot and dense enough, nuclear reactions start. A star is born.