Gas Between the Stars

What Determines its Temperature?

Biman Nath

The interstellar gas in galaxies is heated by stellar radiation and cosmic rays and it also cools through radiation. We take a detailed look at these processes in order to understand the thermal state of equilibrium of the interstellar gas. This gas also manifests itself in different 'phases'– molecular, neutral atomic and ionized, each with its characteristic temperature and density, which we attempt to understand.

They cannot scare me with their empty spaces
Between stars– – Robert Frost ('Desert Places')

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Introduction

Our view of the cosmos a century ago was very different from that now. It had not yet been discovered that we (our solar system) belonged to a galaxy that is distinct from all others (that happened in 1920s). Although it was known (since 1904) that the space between the stars was not quite empty and that gaseous matter filled this 'interstellar' space, but no one knew that a part of this gas was responsible for forming new stars. In fact no one thought about the birth of new stars. The universe looked like an old home of ageing stars; there was no need for new stars to be born.

But the view changed dramatically over a few decades in the middle of the last century, largely due to the work of a few astronomers, that included Lyman Spitzer Jr. Their work revealed that the interstellar space was more like the main stage where the drama of stellar evolution is played out, than an insignificant backstage.

Keywords
Thermal equilibrium, interstellar gas, galaxies.

The discovery of the interstellar gas itself was serendipitous. In

Interstellar gas was first detected by its absorption of light from distant stars which were dimmed and reddened.

1904, Johannes Hartmann in Potsdam, Germany, was observing the binary star system δ Orionis. Two stars orbited around the common centre of mass. When you observe such a system through a spectroscope, you can see the individual stellar absorption lines from the two stars, although separated in wavelength. This is because of Doppler shift, which makes the light waves change the wavelength when the source is moving with respect to us (observers), much like the change in the pitch of an ambulance siren when it zooms past us or towards us. Since the stars orbit around one another, they would periodically recede from us and come towards us. Their individual spectral lines would also keep shifting from bluer side to being redder and back to the blue side. What fascinated Hartmann was not this dance of spectral lines, but a particular line (at 3934 Å) that did *not* take part in this dance. He identified this stationary line as being absorbed by once-ionized calcium atoms, moving away from us with a speed of 16 km/s. This implied that these atoms did *not* belong to the stellar system, but to the intervening medium which was presumably not moving. Hartmann further found that this line was extraordinarily narrow. Usually, spectral lines are broadened by random thermal motions of atoms in a gas (again due to Doppler shifts of the light from individual atoms). The narrow profile of the stationary line suggested that the interstellar gas was quite cold, with a temperature of ~ 100 K.

Over the next two decades, it was established that there were ‘clouds’ in the interstellar space that gave rise to such lines, and that there were roughly three or four such clouds in every 1000 lightyears (LY) along the plane of the Milky Way. Not only calcium, but the presence of other elements was also inferred, such as sodium. There were lines that were traced to molecules like CN. From the observations of dimming of distant stars, it was also inferred that the interstellar gas contained dust particles[1] made of graphites, silicates and other materials. The interstellar space was indeed becoming more interesting by the years.

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[1] See Dust in space, *Resonance*, Vol.8, No.1, pp.15–29, 2003.

1. Interstellar Clouds

By 1951, a key signature of neutral hydrogen was also discovered in the interstellar gas. It had been hypothesized that hydrogen atoms in diffuse clouds would emit a particular radiation of wavelength 21 cm, because of what is known as the hyperfine structure splitting[2] of the ground energy level. The electron could either have its spin aligned with that of the proton in the nucleus, or have it in the opposite direction. The second case is energetically favoured, and the electron is likely to make a transition to this anti-alignment case, emitting a photon during the process. This radiation cannot be detected in the laboratory because the typical time that the electron waits for before making the transition is very long, about 10 million years. In the terrestrial environment, the electron is usually knocked down from the aligned case to the anti-aligned case because of frequent collisions with other atoms. Therefore the electron does not get to radiate the photon, which it would have if it had been allowed to make the transition on its own. But in the tenuous environment of the interstellar space, such collisions are rare, and electrons of hydrogen atoms can safely wait for 10 million years before making the transition and radiating the photon.

This is precisely what the radio astronomers detected. This observation allowed them to map out the distribution of neutral hydrogen in our Galaxy. It was found that there were diffuse clouds which were typically 50 LY in size, separated by 300 LY, and with an average density of $\sim$ 20 atoms per cubic cm. The typical temperature is roughly 100 K, consistent with what Hartmann had inferred.

These observations prod one to ask as to what keeps the clouds heated (or cooled) to 100 K? Why that particular temperature? If it had been heated to this temperature by some process, then why has the process stopped after heating the gas to 100 K? And if the gas has been cooled to 100 K by some physical process, why has the process not allowed the gas to cool further?

The key question was what keeps the interstellar clouds at a stable temperature of around 100 K. Why is this gas in a state of thermal equilibrium?

These are some of the questions that Lyman Spitzer Jr. had asked,

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[2] See The fine structure constant, *Resonance*, Vol.20, No.5, pp.383–388, 2015.

and in a series of papers during 1947–49, he laid out the important processes that heated and cooled the interstellar gas. He found that there was a balance between these processes which led to an equilibrium temperature of around 100 K for the diffuse gas. Of course there were also regions in the interstellar space where gas was heated to much higher (to 10^4, or even 10^6 K) or lower (down to $\sim$ 20 K) temperatures, and we will discuss those phases later in the article. Let us first try to understand the cause behind the 100 K temperature of diffuse interstellar clouds.

2. Sources of Heat

Let us first consider the sources of heating of interstellar gas. One of them is UV radiation from hot (massive) stars. UV photons can ionize atoms and the ejected electron can heat up the gas. However this process is limited to the gas lying close to hot stars, and we will consider this case later in the article. The diffuse stellar radiation that pervades the Galaxy after being scattered by dust grains is not, it turns out, a dominant source of heating.

The most important source of heating of the diffuse clouds are the highly energetic particles that keep zooming through our Galaxy. We detect these particles on Earth as cosmic rays [3], and they consist of protons, electrons and other ions. For protons, for example, the kinetic energy ranges from about 100 MeV to an extremely high $\sim$ 10 J per particle. However, it is the protons at the low energy end (around 100 MeV) that are most effective in heating the interstellar clouds (because the cross-section of interaction decreases rapidly with increasing energy). Calculations show that when cosmic ray particles ionize the gas in diffuse clouds, the ejected electrons have an average kinetic energy of 35 eV.

If this energy of the electrons is shared (by way of collisions) among all the gas particles, then the gas would reach a temperature of $T \sim 35\,\mathrm{eV}/k_B$, where $k_B = 1.38 \times 10^{-23}$ J/ °K is the Boltzmann constant. This would imply a temperature of $\sim 4\times10^5$ K. Of course not all atoms are likely to be ionized. Observations show that only a small percent of the atoms are ionized. How

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[3] See The enigma of cosmic rays, Part-I and II, *Resonance*, Vol.12, No.10, pp 6–17 and Vol.12, No.11, pp 44–53, 2007.

do we know this? When astronomers 'listen' to the radio signals produced by pulsar, they find that their 'pitch' (frequency) alters with time, because of the interaction of electromagnetic waves with electrons on the way. This allows them to estimate the density of electrons in the diffuse clouds, and therefore, the ionization fraction. Given this level of ionization, the resulting temperature (a few thousands degrees K) is too high to explain the observed temperature of 100 K.

3. Coolants

Therefore one must consider the different ways by which a gas can cool in the interstellar space. The most dominant process is that of atoms and ions colliding and exciting the electrons to a higher energy level. Then the electrons come down to a lower level, but in the process they radiate a photon which leaves the cloud. In this way, the kinetic energy of atoms/ions decreases and so does the temperature of the gas. The question is which atoms or ions are important in this process, and which energy levels play the dominant role in sucking out the thermal energy of the gas.

It so happens that a particular line transition in once-ionized carbon atoms is the major coolant in diffuse interstellar gas. These two lines are also an example of a fine structure splitting in atoms.

These fine structure splitting of an energy level comes about because of the interaction between the spin of an electron and the magnetic field due to protons in the nucleus. Consider, for simplicity, the hydrogen atom with one proton. In the Bohr model the electron moves in a circular orbit around the proton. From the point of view of the electron, it is the proton that goes around it, generating a current loop and thus giving rise to a magnetic field. We can try to estimate the split in the energy level from a semi-classical argument, instead of a rigorous quantum mechanical treatment.

If we denote the spin vector of the electron as **s**, then the corresponding magnetic moment is $\boldsymbol{\mu}_s = \frac{e}{m_e}\mathbf{s}$. If the electron is placed in a magnetic field **B**, then the resulting torque would be $\boldsymbol{\tau} = \boldsymbol{\mu}_s \times \mathbf{B}$. Suppose the angle between the two vectors is α. What is the potential energy of the system? We can bring the electron from infinity without doing any work by bringing it along a path that is perpendicular to the force exerted by the field. But after that we must rotate the electron spin axis into the final position. So, the total work done, or the potential energy is $V = \int_{\pi/2}^{\theta} (\boldsymbol{\mu}_s \times \mathbf{B}) d\theta = -\mu_s B \cos\theta = -\boldsymbol{\mu}_s \cdot \mathbf{B}$. Clearly, the potential energy is minimum when the electron spin is aligned with the magnetic field **B**.

Let us now estimate the magnitude of the **B** field. The current due to proton is $I = \frac{Ze}{2\pi r_n / v} = Zev/(2\pi r_n)$. Here r_n is the radius of the electron orbit for the n-th level. From Biot-Savart law, we know that the magnetic field at the electron at the centre of a current loop is $B = \frac{\mu_0 I}{2 r_n} = \mu_0 Zev/(4\pi r_n^2)$. Recall that the orbital angular momentum $L = mvr_n$, and $r_n = n^2 Z(\hbar/m_e c\,\alpha)$, $\alpha \equiv e^2/(4\pi\epsilon_0 \hbar c) \sim 1/137$ being the fine structure constant. Putting all together, we get the potential energy as,

$$PE \approx \frac{Z^4}{n^6} m_e c^2 \alpha^4 \Big(\frac{Ls}{\hbar^2}\Big). \tag{1}$$

Therefore the difference in energy levels in the aligned and anti-aligned cases would be $2PE$. However, this would not apply to $n = 1$ levels, because they have only $l = 0$ states, which are spherically symmetric and there is no preferred axis (which we need in order to set up the direction of the current loop). In the $n = 2$ level, there is $l = 1$ level, where this can be applied. However, for hydrogen in the diffuse interstellar gas, the electron is rarely in the $n = 2$ case, because it takes 10.2 eV energy to take an electron from the ground state to $n = 2$. Therefore we need to consider other atoms/ions.

Consider an ionized carbon atom. It has five electrons and only four can be accommodated in the two $l = 0$ levels (in $n = 1, 2$). The remaining electron must go to the $n = 2$, $l = 1$ state, for which there are two possible fine structure levels. Therefore, every time the carbon ion collides with a free electron, it loses $2PE$ worth of energy in flipping the spin of the bound electron.

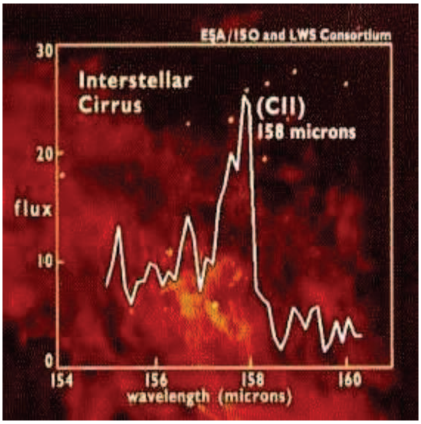

Figure 1. Interstellar clouds have been observed to emit (and thereby cool) a radiation peculiar to singly-ionized carbon atoms at 158 microns (Picture Courtesy: NASA/ESA).

One can then imagine that after a number of such collisions the free electrons in the interstellar gas would be limited in their kinetic energy to $\sim 2PE$ of the once-ionized carbon atoms in the $n = 2, l = 1$ state. From the above estimate, after putting $L = \hbar$, $s = \hbar/2$, $n = 2$ and $Z = 6$, the magnitude of $2PE$ comes out as roughly 0.01 eV, which corresponds to a temperature of $T \sim 0.01\text{eV}/k_B \sim 100$ K!

Carbon may not be a very abundant element, compared to hydrogen or helium, but it acts as a major coolant for interstellar gas, and keeps it at around 100 K as observed. Although for this cooling process to be effective, the radiated photon must escape the gas. For the low density gas in the interstellar region, it is not a problem. And this radiation, which falls in the infrared region, having a wavelength of 158 μm (*Figure* 1), has been observed in recent years, after the advent of infrared telescopes. The diffuse interstellar gas has been seen to 'glow' in this wavelength, which helps it to remain cool at 100 K.

Lyman Spitzer Jr. found that the clue to the thermal equilibrium of the interstellar gas lies in singly-ionized carbon atoms.

4. Hotter Gas in the Interstellar Space

Gas lying close to the birthplaces of massive (and therefore, hot) stars has a different story. Atoms in these clouds are pounded by UV photons that are copiously emitted by hot stars. The hotter a star is, the bigger is the fraction of UV photons emitted by it. Therefore the region around hot star is highly ionized. Spitzer

Figure 2. NGC 604 is a giant HII region in the Triangulum galaxy. This gas is heated by UV photons from hot and massive stars and is cooled by radiation from various ions. A balance between the heating and cooling processes keeps this gas at ~ 8000 K. (Picture Courtesy: NASA).

called the diffuse (almost) neutral clouds 'HI regions', the Roman numeral 'I' signifying that hydrogen is not ionized. And he named the ionized regions around hot stars 'HII regions', a terminology astronomers have since followed.

The main source of heating in HII regions is the UV photons (*Figure* 2). The ejected electrons after ionization has some kinetic energy, equal to the difference between the photon energy and the energy required for ionization. For ionization of hydrogen from the ground state, the ejected electron would have ($h\nu - 13.6\,\mathrm{eV}$) energy. This will be shared among the particles (atoms/ions/electrons) through collisions between them. In the HII regions, this process is balanced by the inverse process of 'recombination', in which a free electron is captured by a lone proton (through Coulomb interaction) and made into a bound electron. The success of this process depends on the electron speed– the smaller it is, the higher is the rate of recombination. In other words, recombination fares better in a relatively cooler gas, when electrons move slowly.

Consider the process of heating in HII regions. UV photons can heat up the gas, but it needs to ionize it first, for which it needs neutral atoms, which, in turn, is supplied by the process of recombination. So, when the temperature is low, recombination is vigorous, and consequently, there is more photoionization, and so energy is pumped into the gas, increasing the temperature. But as the temperature increases, the rate of recombination becomes small, which also brings down the rate of heating. In other words, the rate of heating *decreases* with increasing temperature.

Next consider the process of cooling. Again we need to consider the transition of bound electrons to excited levels through collisions, following which they would come down to a low energy level after emitting a photon, which would leave the gas and thereby cool it. Typically, the difference between energy levels in atoms and ions ranges between a few to few tens of eV. For hydrogen atom, the difference between the ground and the next excited level is 10.2 eV, and the difference between the successive levels are progressively lower. Therefore, when the temperature of a gas is such that $k_B T$ is of order a few eV, or $T \sim 10^4$ K, the electrons can start getting excited to the higher levels, then come down, emit a photon and cool the gas. If the temperature is slightly higher, then energy levels in more ions become available, and the rate of cooling increases.

Given the fact that heating decreases with increasing temperature and cooling shoots up, the situation leads to a 'thermostat' and comes to an equilibrium temperature around 10^4 K. To be precise, the equilibrium temperature is $\sim$ 8000 K because of the presence of other elements, notably OII and OIII (singly and doubly ionized oxygen), as was first shown by Spitzer. If the gas heats up a bit, then precipitous cooling brings it down. If it cools, then heating (which *increases* with decreasing temperature) heats it back up. Therefore, HII regions have a stable temperature of roughly 8000 K.

5. Still Hotter Gas in the Galaxy

The different 'phases' of the interstellar gas – cool, dense and neutral clouds and tenuous, hot, ionized regions – all go about their business, keeping a pressure equilibrium among themselves. Since pressure depends on the product of density and temperature, cooler clouds are denser in general. This rough pressure balance keeps the interstellar gas in a stable state globally. Of course, pressure imbalance can arise in some pockets, which would lead to vigorous gas motions and other associated phenomena.

Interestingly, this equality of pressure, or thermal energy density, also extends to other forms of energy densities in the interstellar space. The thermal pressure of the interstellar gas is comparable to the energy density of cosmic rays, the interstellar diffuse radiation field and even the energy density of the Galactic magnetic field. This global balance leads one to think that all these 'components' of the interstellar space interact with one another in such a way as to keep them in balance. Roughly the energy density is of order of an eV per cc, or $\sim 10^{-12}$ erg cm^{-3}. For example, for diffuse cold clouds, with density $n \sim 20$ cm^{-3} and $T \sim 100$ K, this is roughly the pressure. Also, the average magnetic field in our Galaxy is a few μG, again with an energy density $B^2/(8\pi)$ of a similar magnitude.

Lyman Spitzer Jr. predicted that a part of the interstellar gas is as hot as a million degrees K, which he called the 'coronal gas'.

In 1956, Spitzer pointed out that there were HI (cool, dense) clouds that seemed to be 'floating' above the disc of the Milky Way. The space above the disc was thought to be highly tenuous, if not empty. If these clouds were in contact with a slightly hotter (10^4 K) gas, then one would have detected line emissions from such a gas, as is usually seen from HII regions. This led him to hypothesize that there was a much hotter gas surrounding the disc of the Milky Way, and he called it the 'coronal' gas. He estimated its temperature to be around a million degrees K, which would make it (because of pressure equilibrium) very tenuous. Such a low density gas would not show up in emission. However, if one looked through this coronal gas towards some distant stars, then electrons in some highly ionized atoms, such as five times ionized oxygen atoms may leave a signature by absorbing some UV photons.

There was another hint for the coronal gas. Radio observations had detected a 'noise' that a Russian astrophysicist Iosif Shklovsky had suspected was due to ionized gas that surrounded the disc of our Galaxy. Following the suggestion, astronomers observed our nearest neighbour, the Andromeda galaxy, which is also a spiral galaxy like ours, and detected in 1954 a 'corona' of radio wave emitting ionized gas around it. Spitzer thought a coronal gas would explain this phenomenon as well as the existence of HI clouds.

Spitzer not only hypothesized the existence of this hot gas, but also galvanized the astronomy community into sending a UV detector beyond the Earth's atmosphere, because UV light is heavily absorbed by air. The satellite 'Copernicus', launched in 1972, did confirm Spitzer's haunch about the million degrees gas. Soon, it was asserted that explosions that some stars end their nuclear burning phase with were driving shocks into the interstellar gas, and heating it up to a million degrees in some places.

By that time, the existence of very dense clouds (with particle density of $\sim 10^3$ per cc, much larger than the diffuse HI clouds) came to be established. They are called 'giant molecular clouds'. The temperature inside them is roughly 20 K. In 1950s, it was becoming clear that there were ionized regions around not just single hot stars, but clusters of them, largely through the work of a Georgian astronomer named Viktor Ambartsumian. Others (e.g., Adriaan Blaauw) noticed that some of these stellar associations were near dark and dense clouds. Astronomers wondered if stars formed in clusters inside the giant molecular clouds, which has now become established through direct observations with the help of infrared telescopes.

6. Conclusion

The interstellar space is no longer empty and boring. On the contrary, it has emerged as a storehouse of gas, dust and cosmic rays that in some quarters has led to the formation of stars, and in other places, has been recycled back to the interstellar space after being regurgitated during the final explosion of stars. It has turned out be an important probe of the evolution of our Galaxy, and a stage where the drama of galactic evolution is being played out.

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Suggested Reading

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