Dust in Space

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> *"They cannot look out far./They cannot look in deep./ But when was that ever a bar/To any watch they keep?"*
> – *Robert Frost, 'Neither Out Far Nor In Deep'*

Dust grains in space, which absorb and redden starlight, were once considered to be a nuisance for astronomers, but the study of dust has become important in modern astrophysics. A few interesting characteristics of these dust grains are discussed here.

Mankind has often thought of space and heavenly bodies as being perfect, being very different from terrestrial objects. When we look at the starry sky on a clear, cloudless night, we have the feeling that apart from the stars, space is essentially clear and empty. At least, it does not appear to be as dusty as our neighbourhood on the Earth.

Astronomers were therefore surprised in the last century when they found the first evidences of material in the space between the stars. It was all the more surprising to learn that this material consisted not only of gas atoms or molecules, but also grains of dust. By dust grains, one means solid grains of matter, mostly graphites and silicates, of sizes ranging between 0.005–0.5 μ ($1\,\mu = 10^{-6}$m). How do we know their composition? Or, their sizes, for that matter? Before getting into these details, let us first discuss the observations that led astronomers to conclude that there is dust in space.

Extinction of Starlight

Keywords
Dust grains, cosmic dust, infrared astronomy.

The hints that there was something in between the stars essentially came from the observations that starlight seemed to be absorbed in some directions of sky. Even

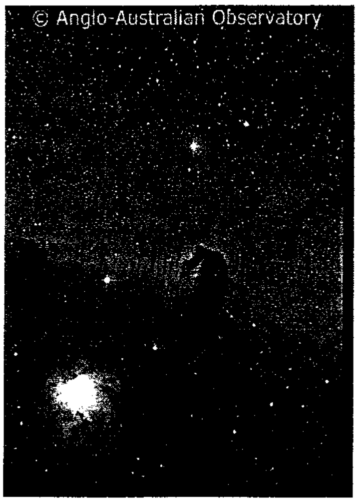

Figure 1. This curiously shaped dark region in the Orion nebula is called the 'horsehead nebula', and is a large cloud of dust that absorbs starlight. The 'neck' of the horse is around 0.75 light year across, and is around 1500 light years from the Earth (Courtesy: David Malin).

William Herschel had noted in the 18th century that there were 'holes in the heaven', meaning that certain portions of the sky seemed devoid of stars. A detailed observation in 1931 by Robert Trumpler showed that there must be light absorbing material in space.

Consider a long, straight road, punctuated on one side by lampposts. Suppose these posts are of equal height, and are placed at regular intervals, and that the lamps on these posts are of equal wattage. Now, if we observe the flux of light coming from these lampposts, and also measure the angle the respective posts subtend at our eye, we would find a definite relation between them. The flux of light would decrease by the inverse square of the distance of the post ($f \propto 1/r^2$), whereas the angle (*i.e.* how big the posts look to us) would decrease by the inverse of the distance($\theta \propto 1/r$). In other words, the flux would be proportional to the square of the angle ($f \propto \theta^2 \propto 1/r^2$). The further a lamppost, the smaller they would appear to us and the dimmer they would look.

Now imagine that the air is not clear, but foggy or polluted. In this case, because of absorption of light, the lamps would appear dimmer than the previous ideal case. The flux would no longer be related to the square of the angle, but higher powers of it. Such a deviation would readily tell us that the air is not clear.

Astronomers similarly found that the flux of light from star clusters (which had more or less similar sizes and similar luminosities) was not proportional to the square of their angular sizes. As a matter of fact, the more distant clusters showed larger deviation from the simple relation. This clearly meant that there was something in the space between the stars that absorbed starlight.

Could it be simple gas atoms or electrons? Astronomers soon found that the observations could not be explained by absorptions from gaseous material. They noticed

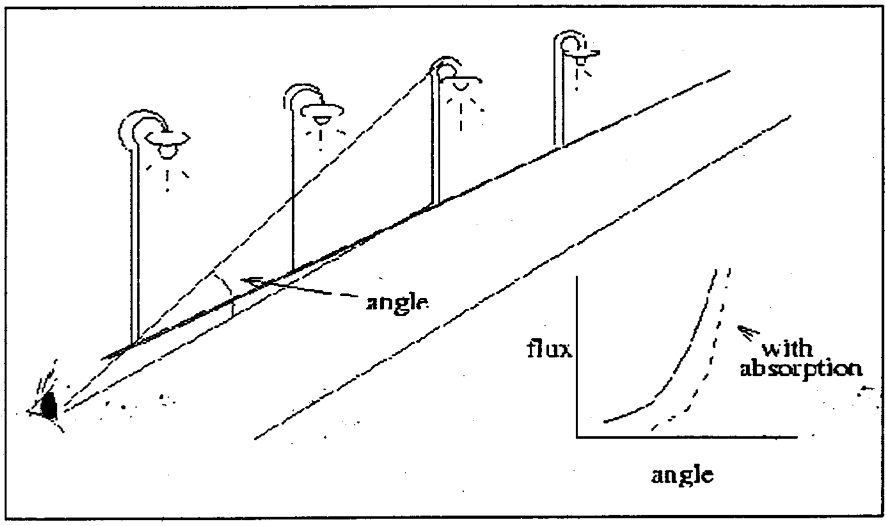

Figure 2. In the case of absorption of light, the relation between angular size and flux received deviates from the simple expectation.

that whatever it was that absorbed starlight, also made it redder. For example, it is possible to know the temperature of the surface of a star from its spectrum. In the stellar spectra, there are absorption lines of elements which can exist only at certain temperatures, and studying these lines one can determine the temperature of the surface of the star. It is thus possible to know the intrinsic 'colour' of the star. Hotter stars are bluer and cold stars are red. But they found that at times even the stars which ought to look blue (considering their temperature from the spectral lines), looked red. This happened especially in the direction of the Milky Way plane, where absorbing material is expected. But the *amount* of reddening was different from what one would expect from scattering off gaseous material.

Consider the scattering of sunlight in our sky that makes the sky blue. Or, the scattering that makes the setting Sun look red. We know that it is because of scattering of light off the molecules in the air (N_2 or O_2, e.g.), which we can think of as bound structures of electrons and nuclei. In this case, one expects light of higher frequencies (such as blue part of the sunlight) to be scattered more efficiently. Quantitatively speaking, the intensity of the scattered radiation is proportional to ν^4 (where ν is the frequency)(see *Box* 1).

Box 1. Rayleigh Scattering of Light

Let us try to estimate the intensity of sunlight after scattering with the molecules in the atmosphere, and its dependence on the wavelength. Let us imagine the binding force between the electron and the nucleus to be due to a spring. The atom will then have a natural frequency, $\omega = \sqrt{k/m}$, where k is the spring constant. (In reality, though, the natural frequency is the transition energy between energy levels divided by $\hbar$, but it is easier to understand a classical model.) The force driving the electron is then,

$$\mathbf{F}_{\text{net}} = m\mathbf{a} = -e\mathbf{E}_{\text{inc}} - k\mathbf{x}\,. \tag{1}$$

We have put a negative sign before k because the spring force tries to decrease the displacement. If $\mathbf{E}_{\text{inc}}$ is sinusoidal with frequency ω, the electrons will also move sinusoidally with *that* frequency, and then we will have $\mathbf{a} = -\omega^2\mathbf{x}$. Putting $\mathbf{x} = -\mathbf{a}/\omega^2$ and $k = \omega_0^2 m$ in the force equation, we can find the acceleration as,

$$\mathbf{a} = \frac{\omega^2}{\omega^2 - \omega_0^2}\left(-\frac{e\mathbf{E}_{\text{inc}}}{m}\right). \tag{2}$$

This basically shows that if the incident frequency is equal to the natural frequency, the atom will oscillate wildly ($a \to \infty$; see curve A in the *figure*). In reality the two frequencies are never equal though, because there is some damping, and one actually has a curve that looks like B in the figure.

The natural frequency for atoms like oxygen and nitrogen is in the ultraviolet. So, the visible frequencies inhabit a region far from ω_0, so that $\omega \ll \omega_0$, and the acceleration becomes $|a| \propto \omega^2$. Since the scattered electric field (due to electron oscillation) $E_{\text{scatt}} \propto |a|$, and since the intensity is proportional to E^2, we have the intensity of scattered radiation, $I_{\text{scatt}} \propto \omega^4$.

For example, the ratio of intensity of scattered light in blue and red is roughly $(\lambda_{\text{red}}/\lambda_{\text{blue}})^4 \sim (6500/4500)^4 \sim 5$. This is why the sky is blue.

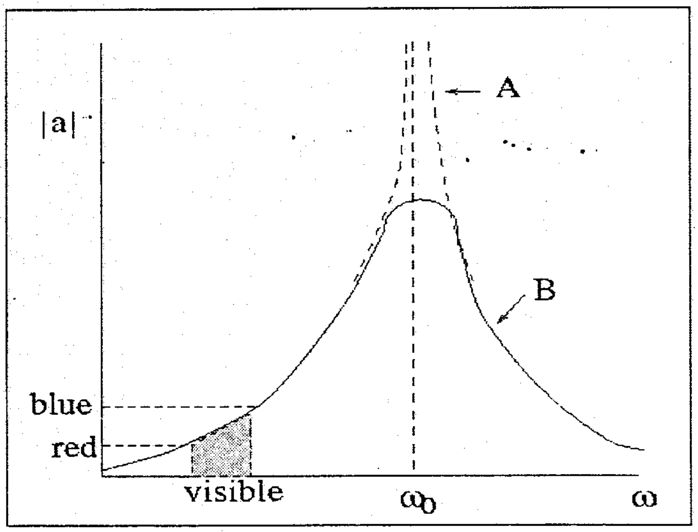

Figure A. Acceleration is shown as a function of frequency of an harmonic oscillator whose natural frequency ω_0 is in the ultraviolet.

One would have expected something similar in the case of interstellar gas (gas in between the stars). But it was found that the reddening is not that strong, and the intensity of the scattered radiation is proportional only to ν. It could not be that this scattering was off large clumps of molecules (instead of single molecules), since in that case one expects the intensity of scattered radiation to be independent of frequency. (It is left as an exercise for the adventurous reader to prove this assertion.) We see this as scattering of sunlight from clouds, which make them look white (meaning that light of all frequencies are scattered equally).

The larger the intensity of the scattered light, the larger is the extinction of light from a particular source in the sky.

But if the size of the clump is not too large, then it is possible to have the intensity of scattered radiation to be proportional to frequency. This is the fact that tells the astronomers about the sizes of the scatterer dust grains.

Roughly speaking, the grains are of similar sizes as the wavelength of the scattered light in this case. Gustav Mie showed with detail calculations that when the size (a) of a scattering particle is comparable to the wavelength (λ) of the light, then the intensity becomes roughly proportional to $a/\lambda \propto \nu$. In other words, for light with very large λ (compared to a), the intensity of scattered light is very small. For light with very small λ, however, the intensity reaches a constant value, independent of λ. One can understand this behaviour by analogy with waves on the surface of a lake. Consider water waves being obstructed by an island. If the wavelength were much smaller than the island, then they would be completely blocked. On the other hand, if the wavelength is much larger than the size of the island, then the waves would pass by almost unaffected.

Another way of describing it is in terms of the extinction cross-section. The larger the intensity of the scattered light, the larger is the extinction of light from a particular source in the sky. One can describe the efficiency of the scattering process in terms of the cross-sectional area of obstruction that the dust grains offer to light. Usually one defines an efficiency factor Q so that the effective cross-section for scattering is $(\pi a^2)Q$, say, for spherical grains of radius a. For Rayleigh's scattering $Q \propto (1/\lambda)^4$, whereas in the interstellar case, $Q \propto (1/\lambda)$.

Polarization of Starlight

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Another convincing argument for the existence of dust grains probably comes from the observation that starlight is polarized in the directions in which there is a lot of absorption, like in the plane of the Milky Way. To understand the effect of dust grains on the polarization of starlight, let us first consider some basic aspects of electromagnetic waves. In an unpolarized electromagnetic radiation, one has the electric fields E_x and E_y (at a given position) varying randomly in time. Consider such a wave passing through an array of conductors as shown in the top section of *Figure* 3. In this case the

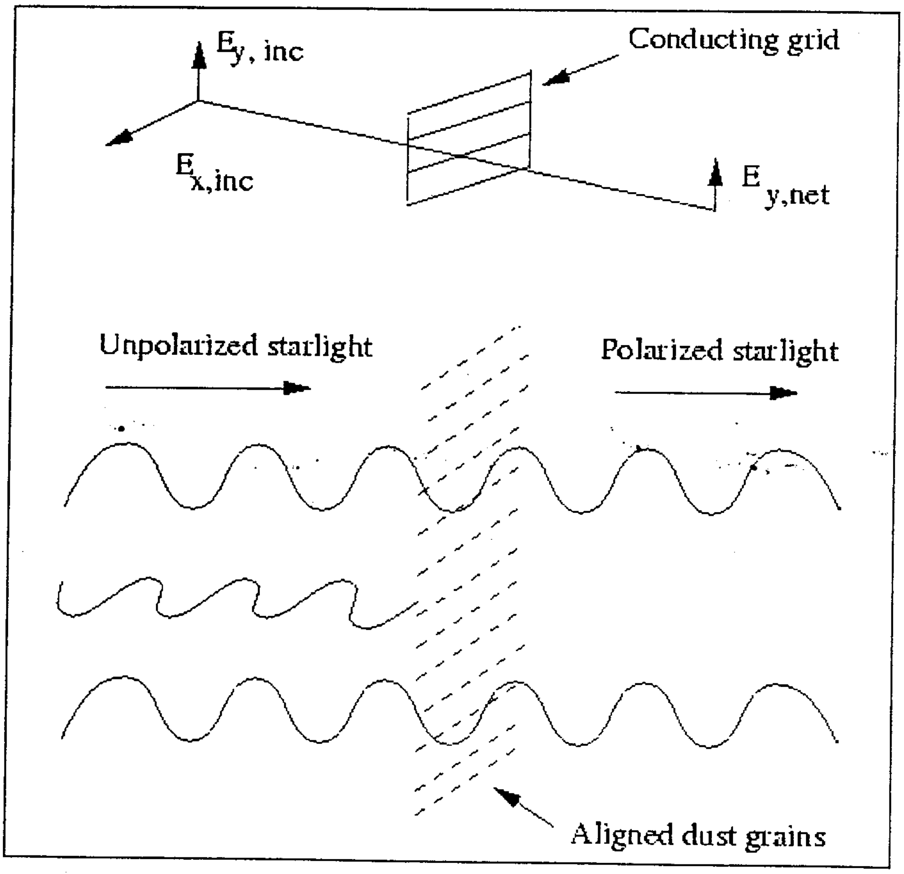

Figure 3. Polarization of starlight as a result of scattering from aligned dust grains is explained.

electrons in the conductors are free to oscillate in the x-direction (supposing that the wires are very thin and have no y-dimension). So, when the wave passes through the wires, the electrons freely oscillate due to $E_{x,\mathrm{inc}}$ (driven by the force $F_x = -e\,E_x$). This oscillation produces a radiation with an electric field which is opposite in direction to the incident $E_{x,\mathrm{inc}}$. This is because the new, scattered electric field is proportional to the force driving the oscillation, which is opposite in direction to the incident field.

Now, the net field after passing through the grid is given by $E_{x,\mathrm{net}} = E_{x,\mathrm{inc}} + E_{x,\mathrm{scatt}}$. Here $E_{x,\mathrm{scatt}}$ is opposite to $E_{x,\mathrm{inc}}$, and if there are enough wires, then one would have a complete cancellation of these two terms. In the y-direction, however, there is no scattered radiation (since electrons cannot oscillate in that direction) and there is no cancellation there. Finally, one ends up with radiation in which the electric field oscillates only in one direction, in other words, a polarized radiation.

Originally light from stars is unpolarized. When astronomers first noticed that starlight was partially polarized in the plane of the Milky Way, the most obvious explanation was that there was something like the conducting grid in its path. If there are dust grains which could be somewhat elongated and conducting and there was something that could align them, then one could easily explain the polarization observations. One way to align them is by the ordered magnetic field in the Milky Way plane (whose strength is about a millionth of that found on the Earth), if the grains were themselves magnetic. Then the dust grains would align with the field and make the starlight polarized.

(Incidentally, the polaroid filters used by photographers have specially aligned elongated molecules to allow the passage of waves with electric fields oriented in a specific direction.)

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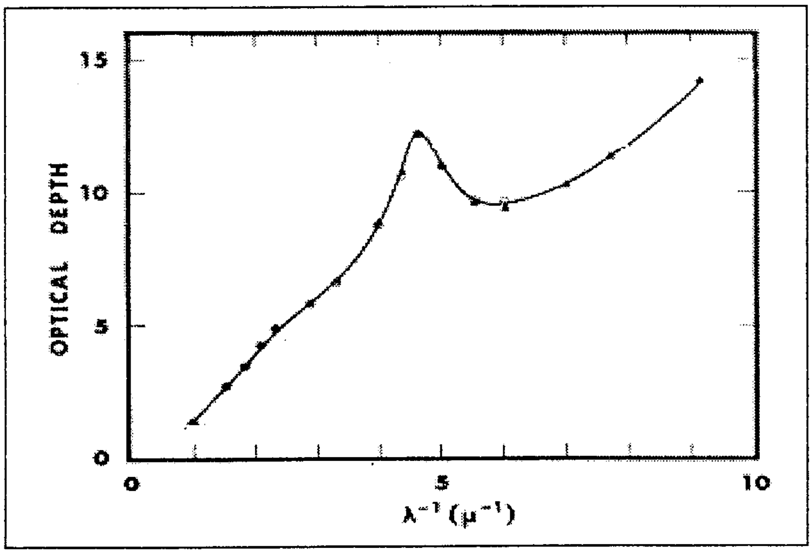

Figure 4. The dependence of starlight extinction on wavelength in the interstellar space is shown here (adapted from Mathis, Rumpl and Nordsieck (1977, Astrophysical Journal, vol 217, pp.425)). The extinction is shown in terms of the optical depth, which is proportional to the amount of absorption. Notice that the x-axis plots the inverse of the wavelength.

Composition of Dust Grains

Going back to the extinction of starlight due to dust, the observed dependence of extinction with the wavelength is not very simple. At longer wavelengths (the left side of the plot in *Figure* 4), the data agree well with the scattering calculations by Mie. At wavelengths shorter than that of blue light, however, the data begin to deviate from the expected relation. A conspicuous deviation in the form of a 'bump' is evident at 2175 Å. This 'bump' has given the astronomers some clue as to the composition of the dust grains. Graphite, an ordered form of carbon, interacts strongly with light near 2175 Å, although it is not very clear how carbon could organize into large graphite particles in the space between the stars. But the 'strength' of the 'bump' does suggest that graphite could be a major component of the interstellar dust.

There are also indications of other elements in the grains. When one looks at the spectra of stars, one finds some spectral lines, or bands, which are due to absorption by material in the interstellar space. Of course there are also spectral lines from absorption by material *in* the stars. But if one observes these lines from, say, a system of binary stars revolving around one another, then these lines (from stars) would shift their frequency with a periodicity as a result of Doppler shift. The lines arising from the interstellar gas would also be shifted due to the random motions of the gas clumps, but they would stand out in the background of the regularly shifting lines from the stars.

Among these interstellar lines, there is a peculiar feature at 9.7μ m and 18μ m, which is thought to be the result of stretching of the Si-O chemical bond and the bending of Si-O-Si bonds, respectively, in silicates. In quantum mechanics, the energy levels of atoms are quantized, and similarly, the energies associated with chemical bonds are also quantized. In the latter case, though, the energy levels are bunched together closely to form 'bands', producing broad spectral features. The above mentioned absorption features therefore indicate that silicate grains are also present in dust grains. Some observations also seem to require the presence of dirty ice (H_20 containing impurities) and ammonia.

There are also some emission bands, most probably due to vibrations in C-C and C-H bonds, which give clues to the existence of organic benzene ringlike molecules, which are called polycyclic aromatic hydrocarbons (PAHs). There is a lot of research going on these days on the existence and role of these molecules in the physics and chemistry of the interstellar matter.

One famous example of the usefulness of such studies is the discovery of the Buckminster fullerene molecule (C_{60}), which is the third form of carbon (after diamond and graphite). In their attempt to understand the formation of long carbon chain molecules in the interstellar space, Harry Kroto, Richard Smalley and Robert Curl serendipitously discovered the Buckminster fullerene molecule in laboratory (for which they were awarded the Nobel Prize in 1996).

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Box 2. Interaction Length.

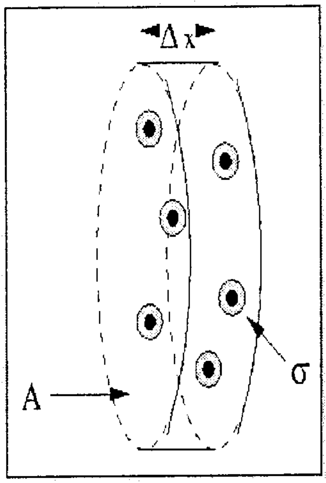

Figure B. The concept of interaction length is explained.

Let us suppose that the number density of particles is n (number per unit volume). Consider a slab containing $N_1 = n\,A\,\Delta x$ particles, where A is the area of the face of the slab, and Δx is the thickness (see *Figure* B).

Suppose the interaction cross-section is σ. We can then imagine an interaction area σ surrounding each particle. If we look at the slab end on, the total interaction area will be σN_1. For a photon striking this slab, the probability of an interaction between this photon and any of the particles, is

$$probability = \frac{\text{Interaction area}}{\text{Total area}} = \frac{\sigma N_1}{A} = \sigma n \Delta x\,. \qquad (1)$$

We can define an 'interaction length'(l) to be the distance that a photon must travel such that the probability of its interacting is almost unity. Putting the above probability equal to unity, and writing $\Delta x = l$, the interaction length, l, is given by $l = \frac{1}{\sigma n}$.

How much Dust is there?

One can estimate the amount of dust in interstellar space from the observations of starlight extinction using simple arguments. First, it is clear that dust is the principal cause of extinction of starlight in the visible band, as we have discussed earlier. For simplicity, let us assume that the cross-section for absorption of photon is roughly the geometrical cross-section of grains, and, assuming spherical grains (which is not quite correct in reality!) of radius r, we can use a cross-section of $\sigma \sim \pi r^2$. Let us suppose there are n such grains per unit volume. The typical photon interaction length is then given by $l \sim 1/(n\sigma)$ (see *Box* 2). From the observations, astronomers estimate that it takes about 1000 light years of interstellar material to produce one photon interaction length. Using $l = 1000 \times 10^{16}$ m (1 LY=10^{16} m) and $\sigma = \pi(5 \times 10^{-7}\text{m})^2$, we have,

$$n \sim \frac{1}{n\sigma} \sim \frac{10^{-7}}{\text{m}^3} \sim \frac{10^{-13}}{\text{cc}} \qquad (1)$$

We should compare this with the typical number of hydrogen atoms in the interstellar space, which is about 1 per cc. Curiously, this simple estimate shows that the interstellar space is quite a dirty place compared to the Earth's atmosphere. Our air is polluted by only one dust particle for about every billion billion (10^{18}) atoms of atmospheric gas. If we compressed a typical portion of interstellar space to equal the density of air on Earth, this portion would contain enough dust to make it difficult for us to see our own palms held at arm's length. (Compared to the density of almost 10^{19} atoms per cc in our atmosphere, the typical density of the interstellar space is about one atom per cc.)

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With the ideas of composition of dust grains that we discussed earlier, the density of dust grains is estimated to be around a few grams per cc. This estimate, along with the estimate of their sizes, leads one to the estimate of the total mass of dust grains in our Galaxy. It turns out that dust grains contribute to about a percent of the total mass of the interstellar material (which in turn is about a percent of the total mass of the Galaxy, including its invisible, dark matter).

If one compares the mass ratio of dust and gas, one finds that mass in dust grains is about one hundredth of that in gas. Now, the fraction of mass of the interstellar gas that is in elements heavier than hydrogen and helium is also about a hundredth of the total. It leads us to the conclusion that most of the heavy elements in the interstellar medium is locked up in dust grains as opposed to being in diffuse gas. Detail observations also confirm this conclusion.

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Dust and Formation of Stars

This amount of mass distributed in the form of dust grains may sound too small to matter at all. It is indeed negligible when it comes to the dynamics of the Galaxy. But it is not so in the case of dynamics of, say, gaseous

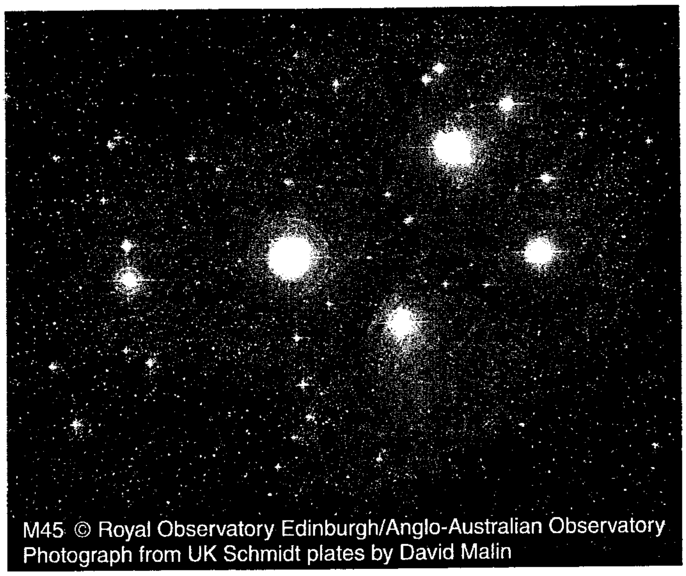
M45 © Royal Observatory Edinburgh/Anglo-Australian Observatory
Photograph from UK Schmidt plates by David Malin

Figure 5. The 'reflection nebula' in the constellation of Pleiades ('Seven sisters'), which shows blue starlight from young stars being scattered by dust particles (Courtesy: David Malin).

nebulae, which exist in the interstellar space (see *Figure* 5). When radiation falls on a dust grain, the grain gets accelerated, because of the absorption of the photon by the grain. Since the dust grains are constantly colliding with gaseous particles, it also drags along gas with it. Sometimes this turns out to be a very efficient way of transferring the radiation energy to the gas as its kinetic energy in this way, via the dust grains embedded in the gas. As a matter of fact, astronomers suspect that dust grains can even drive powerful winds out of galaxies.

Not only the dynamics, but dust grains also affect the temperature of the gaseous material surrounding it. It can heat up the gas, when powerful ultraviolet starlight falls on it and ejects electrons from the grain by photoelectric effect, and when these electrons impart their energy to the gaseous particles in the vicinity. It can also aid in the cooling of the gas. By the cooling of gas, one means electrons coming down to low energy levels and radiation leaking out of the gas in the process. For this to happen in the first place though, there must be low energy levels to come down to! It is difficult to cool below a few thousand degrees (Celsius) using atomic energy levels. Typically the difference in atomic energy levels is of order a few eV, which corresponds to about

10^4K. Below such temperatures, one must use energy levels in molecules. Since they have more structures than atoms, they have energy levels due to vibration and rotation of atoms, which have smaller energy differences.

But for even this to happen, one must first form molecules! Gas is so tenuous in the interstellar space that it is difficult to form molecules there, since atoms first need to collide to form molecules. In this regard, dust grains can be very helpful. They provide their large surfaces for atoms to stick for a while, in order to meet other atoms to form molecules. In fact, without the presence of dust grains, it would have been extremely difficult to form molecules in space. Without molecules, it is therefore impossible to cool gas below thousand degrees or so. And without such cool gas, it would have been impossible to form stars.

In fact, without the presence of dust grains, it would have been extremely difficult to form molecules in space.

Stars form out of gravitational collapse of gaseous clouds. If the cloud is hot, then the thermal pressure of the gaseous particles (arising from their random motions) would try to balance the gravitational force directed inward. Gravitational collapse can only occur when the gas has cooled down so that gravity wins. (Later, of course, the contraction due to gravitation would fire thermonuclear reactions in the core, lighting up the star.)

Dust grains are, therefore, essential in the process of star formation. Incidentally it is also the stars that produce these dust grains in the first place. We have learnt how difficult it is to form molecules in the interstellar space. Surely, it must be even more difficult to form huge dust grains there. According to astronomers, relatively cool surfaces of cool stars (like red giants) are where most of the dust grains are formed. Lot of such stars show infrared emission in excess of expectations, which is thought to be due to nascent dust grains.

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Infrared Astronomy

The properties discussed so far have made the study of dust grains very attractive to astronomers. They are no longer regarded a nuisance, blocking useful information from starlight. In fact, the next generation telescopes which are being planned now, focus on different aspects of the study of dust grains.

Careful readers may find something puzzling here; if dust grains are formed around stars, and dust grains are needed to form stars – which came first in the Universe? Naturally, the first stars in the Universe must have formed without the aid of dust grains (more precisely, without the aid of molecules formed on dust). Recently, there has been a lot of interest in the study of the first luminous objects in the Universe, and for these one needs to find ways to form stars without dust grains. It is believed that the abundance of molecules and dust grains slowly increased as the Universe became older. (Calculations of such evolution require not only the knowledge of the formation of dust grains, but also how the grains are destroyed. Usually collisions between grain and high energy particles slowly destroy the grain by ridding it of its constituent particles, a process known as 'sputtering'.)

If we recall the nature of starlight extinction by dust grains, the intensity of scattered radiation is large for longer wavelengths (longer waves in the lakes simply passing by the island in the analogy). This means that dust grains leave longer wavelength radiation, like infrared light, almost unaffected. Using infrared rays for astronomical purpose is, however, difficult. The infrared rays from stars get absorbed in our atmosphere, and one needs to send detectors in the upper atmosphere by balloons or send infrared telescopes abroad satellites. The techniques of detecting infrared photons are also difficult. It is only recently that it has become possible

Suggested Reading

[1] **Aneurin Evans, *The Dusty Universe*, Ellis Horwood, New York, 1993.**

[2] **Lyman Spitzer, *Searching between the stars*, Yale University Press, 1982.**

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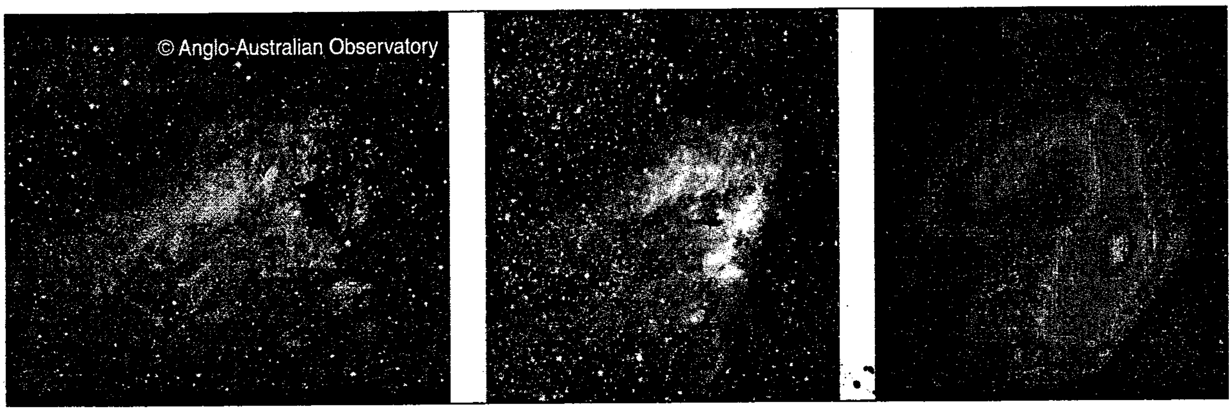

Figure 6. The image of a diffuse nebula (M17, in the constellation of Sagittarius, also known as the Omega nebula) is shown here in three different wavebands; in visible light (left; courtesy of Anglo Australian Observatory), in near infrared (center; courtsey of 2MASS/UMass/IPAC-Caltech/NASA/NSF) and in far infrared (right). The striking difference between the left and the center images is that the dark cloud in the lower right portion has vanished in the infrared image. This shows that the dust cloud that was absorbing visible light, is transparent to the infrared light, showing the power of infrared astronomy. At longer wavelengths (image on the right; courtesy of IRAS project IPAC-Caltech), however, the same dust cloud becomes a emitter, glowing as a result of its own temperature, showing another aspect of infrared astronomy. The infrared images (center and right) are colour coded (since we cannot perceive infrared rays!). The centre image is coded to mimic what the human eye would see, with hot stars in blue. In the far infrared image ($\lambda \geq 5\,\mu$m) on the right the brightest region is shown in red and faintest in blue.

to do infrared astronomy at the levels of sophistication of other branches of astronomy. A few satellites have already given astronomers glimpses of the galaxy (and beyond) that was impossible with visible light, because of dust extinction.

What is more is that infrared rays can also reveal the glow of the dust grains themselves. Every object emits radiation characteristic of its temperature. It is possible to estimate the temperature of the dust grains from the considerations of heat absorbed (from absorption of light) and heat re-radiated by it. Naturally, these two processes depend on the amount (and spectrum) of starlight received by the grain, and on the composition of the dust grain. Depending on the region where the dust grain finds itself, astronomers estimate that the temperature of the grains ranges between 10–100 K. Now, objects with temperature in this range emit radiation in the infrared region. Again, infrared astronomy becomes an important tool in learning about the physical characteristics of the dusty region (see *Figure* 6).

Astronomers are eagerly waiting for the launch of the Space Infrared Telescope Facility (SIRTF) in January 2003, which is expected to usher in a new era in infrared astronomy, with its ability to detect infrared photons in a wide range of wavelengths (3–180μ m) and its sensitivity. Plans are also afoot to launch the Next Generation Space Telescope (NGST), which will mainly be an infrared telescope, by 2007.