

13 June 2012

**Star Dust**

Professor Carolin Crawford

This lecture focuses on one of the more surprising – and perhaps rather less glamorous – ingredients of our Galaxy: dust. Dust is everywhere. It is responsible for deep dark drifts that trace the arms of a vast spiral galaxy, opaque knots studded across the background glow of a gaseous nebula, and bright tails of comets as they fall through our Solar System.

Star dust is, of course, very different from the household dust we experience in everyday life. It is made from aggregates of tiny solid grains of matter, where each grain has a characteristic size of around a tenth of a micron, a similar size to the particles in cigarette smoke. The dust is predominantly composed of carbonates (in the form of graphite) and silicates, and individual grains may be coated with an icy layer of volatile compounds such as frozen water, ammonia or carbon dioxide. The mass contained in the dust clouds is around a thousandth of that contained in the visible stars in a galaxy.

Cosmic dust was late to be discovered, and originally it presented an annoying complication for observational astronomers. With modern advances in infrared detection, however, we can now observe dust directly, and map out its key contribution in the lives of galaxies. Dust has come to be acknowledged as a significant and vital component of astrophysical processes; in particular, the formation of the stars and planetary systems.

The Discovery of Cosmic Dust

It is not obvious to the unaided eye that there is dust out in space. The dust is embedded in interstellar gas to create invisible clouds that can be light-years across, and containing sufficient grains to obscure the background light of stars. Such dark structures become apparent against the diffuse light of the Milky Way, but early astronomers assumed that such gaps in the light were created by a deficit of stars, or ‘holes in the sky’. This lack of understanding often misled their interpretation of observations. For example, Sir William Herschel attempted to map out the shape and size of the Milky Way in 1785, by carefully counting how many stars could be seen in a variety of different directions away from the Sun. From fewer stars along a line of sight he concluded that he was looking to the edge of the Galaxy, and a direction with many more stars implied that he was looking deeper into the Milky Way. Although his survey of star counts did correctly deduce that the Galaxy was flattened, he was in error about its size and shape due to a couple of incorrect assumptions. He didn’t realise that stars vary widely in luminosity, and that space is not completely empty or transparent. This means that one can’t just assume that a star is fainter because it’s further away; it could either be an intrinsically fainter type of star, or its light may have been dimmed by an intervening screen of interstellar dust.

It wasn’t until the late 1800’s and early 1900’s that the American astronomer EE Barnard began to systematically catalogue and study the dark patches that interrupted the starlight, using the new technique of photography. He was the first to suspect that rather than being due to gaps between the stars, these dark regions were due to clouds of obscuring matter. Only in the 1930’s, however, was the presence of interstellar matter and its effect on the results obtained from observations demonstrated. Robert Trumpler was measuring the distances to bright clusters of young stars in the spiral arms of our Galaxy as a way of mapping out its shape, and he used two independent methods to do so. He discovered that the more remote clusters were systematically dimmer than might be expected from their distance, showing that there was an intervening screen of material that obscured some of the light.

**The effects of dust**

Extinction by dust

The dust mixed in with the interstellar gas thus obscures and dims the light of distant objects, an effect we call extinction. This can confuse an observer into overestimating distances based on the luminosity alone. Within a spiral galaxy, the dust is particularly concentrated to the plane of the flat disc; indeed, when such a system is viewed edge-on to our line-of-sight, the dark dust lanes can appear to divide a galaxy almost into two. The dust clouds thus complicate observations of the most active and interesting regions of massive star formation in the spiral arms. Additionally, as we ourselves live within the disc of the Milky Way, the dust in the disc completely blocks our view of the centre of the Galaxy, rendering it very difficult for study.

Reddening/scattering by dust

From his observations of clusters, Trumpler also realised that the intervening dust doesn’t only extinguish the light of the distant stars, but it also affects the colour of that light. The dust particles selectively diminish the bluer wavelengths in a process known as Rayleigh scattering. Photons will bounce off particles in their path – whether atoms, molecules or small clumps of molecules – to be scattered away from their original direction. The consequence is that some of the photons that were travelling from a star towards us are then redirected away and no longer reach us. This scattering process doesn’t happen evenly to all colours, however, as light can only be scattered by particles of a similar or larger size than its wavelength. The tiny size of a typical interstellar dust grain (below half a micron in diameter) means they scatter the shorter, bluer wavelengths most efficiently. Consequently more blue light than red is removed from the star’s light as it travels through a dusty cloud, making the starlight that emerges appear redder.

The more dust along the line of sight to an object, the dimmer and redder it will appear. The situation is further complicated by the way that dust is only patchily distributed across the sky, and so it is not always straightforward to determine whether extinction and reddening effects are due to a larger volume of intervening space or just a particularly dense foreground dust cloud. The reddening is a subtle effect that isn’t apparent with the unaided eye – it requires telescope images to be detected. [It should also not be confused with the Doppler effect of the reddening of a spectrum due to an emitting object receding from us at speed.]

Reflection Nebulae

The scattering and reddening is a similar process to that which gives us red sunrises and sunsets here on Earth. When it is appears near the horizon, we observe the Sun through more of the densest layers of our atmosphere (those closer to the Earth’s surface), resulting in increased scattering by molecules of air, and blue light lost - turning the Sun much redder than when it is observed at higher altitude. The effect is enhanced when the atmosphere contains extra localised scattering particles, such as ash or dust. The blue light that has been scattered out of the sunlight into all directions can be seen during the day as our sky. In the same way that this scattered blue light renders the atmosphere visible to us here on Earth, scattered blue light can also reveal the presence of a dust cloud in space.

A dust cloud close to a bright star may be distributed in too low or too patchy a concentration to heavily obscure the starlight that is directed towards us. However, the blue wavelengths of the starlight has been scattered into all directions by the dust. Some travels towards us, revealing the surrounding cloud as a distinctly blue reflection nebula. Stunning examples include both the ‘Iris’ nebula (where a dusty cloud morphs from a veil of obscuration to a glowing blue ghost in the proximity of a massive hot young star) and the dramatic profile of the ‘Witch’s Head’ nebula close to the bright star Rigel in Orion. The obvious blue hue of the Pleiades is not just due to the colour of the forty to fifty young stars that make up the cluster, but also to the way that their blue light is scattered by a neighbouring dust cloud.

**Direction Detection of Dust**

Infrared Radiation

The dust grains can, however, also be directly detected. Most of the dust in the diffuse interstellar medium is incredibly cold, and radiates in the far-infrared, at wavelengths beyond 100 microns. Where the grains obscure and absorb the energy of nearby starlight, however, their temperature is raised to a few tens or hundreds of degrees above absolute zero. Objects at this temperature (including humans!) radiate brightly at mid-infrared wavelengths. Thus dark obscuring clouds that block the light of stars in optical images become incandescent when observed with an infra-red telescope, revealing their inherent structures and shapes. Despite representing only a tiny fraction of the total mass in our Galaxy, dust grains absorb roughly 30-50% of the starlight emitted to then re-radiate it as infrared emission. This means that the dusty component that is only a thousandth of the ordinary (baryonic) mass within the Galaxy produces from a third to half of its total observable luminosity! Dark patches of dust that reveal their presence in the visible waveband only by a paucity of background stars, and a faint trace of glowing pink hydrogen gas, can be seen to shine in infrared light as towering pillars of dust and gas.

Seeing through the dust

The infrared waveband not only reveals the distribution of the dust clouds, but permits more penetrating observations of what is contained within it. Remember that it is the shorter wavelength (bluer) light that is most efficiently scattered by the dust grains; the longer (and redder) the wavelength of light, the more it can travel through clouds of dust relatively unimpeded. This becomes particularly true at the longest, infrared wavelengths. Thus often it is only the infrared light given off by stars tucked deep inside dusty clouds that can completely escape to be detected, unlike the visible radiation. Hence infrared observations can penetrate through a dusty cloud to reveal new clusters of stars still forming deep within the densest, most obscured parts of a nebula. Infrared astronomy thus also provides a way to observe the star formation occurring within the spiral arms of nearby galaxies, and the central regions of our Galaxy that would otherwise by heavily hidden from our view.

Origin of the dust

The distribution of the dust is confined to the flat disc of a spiral galaxy, and this (and indeed, the lack of it in an ordinary elliptical galaxy) gives us the first clue that it is intimately associated with massive stars. The physical conditions in interstellar space are not thought to be favourable for the formation of the grains – at such temperatures it would take much longer than the age of the Universe for them to form. Instead, it is thought that stars create the dust as they die.

Dust from giant stars

The chemistry for dust formation requires that the right elements are brought together in a reasonably cool environment, such as that found in the extended outer layers of red giant stars. The red giant phase is a very late, evolved stage of a star’s life, where its atmosphere becomes inflated and diffuse. Consequently the star swells to an enormous radius, and the surface temperature drops to around 5000K or lower. Material at the surface is only now loosely bound by gravity. This period of a star’s life is characterised by instability, and by massive stellar winds, whereby a star can lose from a millionth to a thousandth of a Solar mass per year (which is at least a million times more than the mass loss from the Sun in its Solar wind).

We observe many such giant stars to be surrounded by large clouds of gas and dust, such as the famous red giant Betelgeuse in Orion. If placed at the centre of our Solar System, the diameter of the star itself would encompass the orbit of Jupiter; it is surrounded by an even larger cloud of circumstellar dust that would stretch some 400 times the Earth-Sun distance. Another example is the complicated shells of matter that surround the carbon-rich star CW Leo, which is the brightest object (apart from the Sun) at mid-infrared wavelengths. Images show that the shape of the surrounding dust clouds can evolve on timescales of just a few years. One of the largest and most luminous supergiants known, VY Canis Majoris, has had many outbursts that have ejected huge quantities of gas and dust into space over the last thousand years or so; it is now embedded in a large extended cloud. Strong infrared emission provides information on the properties of the dust grains (and many molecules) within this cloud.

The surrounding dust clouds can absorb the light from the underlying star, and thus modify its spectrum by imprinting absorption features characteristic of particular chemical properties of the grains. In addition, the grains are also warmed in the proximity of the star, and can radiate strongly in the mid-infrared, producing emission features. Thus several specific spectral signatures are available to identify the chemical composition of the emitting or absorbing dust particles. Broad features at 9.7 and 18 microns are attributed to the stretching of bonds in silicates (similar to many types of minerals found in the Earth’s crust); narrower features around 11.3 microns point to rarer substances such as silicon carbide in the environment of much more carbon-rich stars. There may well be other types of dust present beside the silicates, but these don’t necessarily produce such clear signatures in the spectrum. However, infrared spectra do also detect features that result from the bending and stretching modes of large and complex carbon molecules such as aromatic carbon (graphite, or polycyclic aromatic hydrocarbons —PAH), suggesting that molecules also form in the extended atmospheres of these giants.

Planetary nebulae

The red giant phase of a star’s life prefaces its eventual demise, when the supply of available fuel at sufficiently high temperatures is exhausted, and nuclear fusion can no longer continue to support the star against the inward pull of gravity. The core of the star implodes, shrinking to become a hot white dwarf. The outer atmosphere is then heated and driven off into space in a superwind that forms a rapidly expanding bubble of material known as a planetary nebula. This shell of gas is heated by the white dwarf to temperatures where it will radiate brightly in the optical wavebands, revealing shells or compact knots of dust embedded in the structure. Famous examples that show the dust include the ‘Ring’, ‘Cat’s Eye’, ‘Eskimo’ or ‘Helix’ planetary nebulae. Others such as the ‘Butterfly’ nebula show how an obscuring ring of dust pinches the nebula at its centre. Shed in an earlier mass loss event, this dust subsequently constricted the star’s destructive outflow into a more hourglass rather than spherically symmetric shape.

Molecular clouds and globules

The matter shed by the giant evolved stars – both dust grains and the heavy elements built up by nuclear fusion in the heart of stars – becomes mixed in with the gas of the surrounding interstellar medium. The dust not only thus becomes part of the reservoir from which new stars form, but it plays a pivotal role in prompting that star formation to occur in the first place. The dust is an important ingredient of the nebulae that surround blue star clusters. These young massive stars have only recently (ie within a few million years) condensed from the core of a diffuse interstellar cloud. Their energetic light now heats the surrounding remnants of this gas, prompting it to radiate in the characteristic pink glow given off by excited hydrogen. Where the dust is mixed in with the gas, it can contribute both obscuring tendrils of material, and blue reflection nebulae from the scattered light.

Molecular clouds

Within these nebulae, regions of particularly heavy dust concentration show as completely opaque knots (sometimes known as ‘globules’) silhouetted against the pink background glimmer. These are the densest regions anywhere in the interstellar medium (although they are still nowhere as dense as the air we breathe here on Earth!). However, the high density of dust grains in these small clouds not only prevents the light of the nearby stars from passing through the cloud, but they also shield the core of the cloud from the stars’ heat. Without an internal heat source, the temperature in the densest parts of the cloud can thus drop to only a few degrees above absolute zero. Under these conditions the atoms in the cloud can form molecules, with the dust grains acting as reaction sites. The most common molecule formed is hydrogen, but many more complex (such as water, ammonia and methanol) molecules are also present. Any one interstellar molecular cloudcan have a size ranging between a few and fifty light-years, and contain a mass of up to a thousand times that of the Sun. The light and winds from the nearby massive stars have a harsh corrosive effect on these clouds, eroding them from the outside to give them a jagged appearance. Eventually only the densest pockets resist the erosion, and they are revealed as small, dark dusty globules as the cloud around them is gradually eaten away.

The role of dust in star formation

The shielding presence of dust creates the coldest, densest pockets within the ISM, which in turn provide the ideal locations for star formation to occur. Whether or not a gas cloud collapses under gravity depends on a delicate balance between two physical properties: its density and its temperature. Every atom or molecule in the cloud is pulled on by the combined gravitational attraction of its neighbouring particles, and thus any slightly over-densities will produce a slightly stronger gravitational pull on surrounding matter towards that region. As it attracts more material towards it, it will become denser, more massive and gravitationally stronger... and so a runaway process of gravitational collapse is triggered. The denser a region, the more prone it will be to collapse under gravity. This process can be resisted by the outwards thermal pressure of the particles in the cloud. Even if at only a few degrees above absolute zero, these particles are in continual motion – the temperature of an ensemble of particles is only a measure of how much kinetic energy they have – and such motions can enable them to resist any local gravitational pull.

Thus whether or not a cloud of a certain size and temperature will collapse to form stars depends on it being above a certain density in order for gravity to overcome the thermal motions of the particles within it. This threshold density is higher the warmer the cloud. (There are, of course, other factors, such as the strength of any magnetic field threading through the gas, or the amount of rotation present, which can also act to inhibit a cloud’s collapse under gravity.) The conditions for star formation are most favourable in the very coolest and densest environments, such as those provided in the cold dusty globules. Within any molecular cloud, the globules can fragment to provide many condensations, each collapsing at an accelerating pace to form stars. The presence of the dust does also mean that it is near impossible to directly study the process of star formation, unfortunately, until we can make observations using the new generation of high-resolution infrared telescopes, such as the planned James Webb Space Telescope.

**Planetary Discs**

Proplyds

What we do observe of the beginnings of the star formation process is encased in dusty proplyds, such as those discovered in the Great Orion nebula. This nebula is formed from a cavity excavated by the winds and light form very young stars has burst through the side of a giant molecular cloud some 1,500 light-years away, to give us a glimpse into a very active stellar nursery. The cavity is surrounded by a shell of dust, and the infrared observations reveal not only the glow from these dust grains, but also the presence of thousands of young stars buried in some of the more obscured regions of the nebula. Within the large swirls and rifts of clouds of gas and dust comprising the nebula, opaque cocoon-like structures can be seen, either in silhouette against the bright background light or illuminated by the nearby stars. These are known as proplyds (where proplyd is a shortened form of ‘protoplanetary disc’), and represent the earliest stages of the formation of a planetary system around a star. Such proplyds are found swirling around at least half of the newly formed/forming stars in Orion; when they were first discovered in the mid 1990’s, they were the first indication that planetary systems round other stars could be common throughout the Galaxy.

Observations of these proplyds conform to theories that our own Solar system was formed from a similar disc of dusty material some 4.5 billion years ago. The very centre of the cloud, where it is densest, is falling together under gravity. The gravitational potential energy is converted to heat, and as matter continues to rain down into the core of the cloud it will heat up until it temperatures of millions of degrees are reached. At such temperatures the process of nuclear fusion that powers a star will begin, and a protostar is formed at the core. More massive stars are made more rapidly – it takes about ten million years to form a star similar to our Sun, but only about a hundred thousand years for a star some ten times more massive.

When the protostar ‘switches on’, it is still surrounded by the remains of its cocoon, which has settled to form a vast and thick disc of gas and dust around the star. The proplyd can easily contain anywhere from one to a thousand Earth masses’ worth of material. Whether the proplyds we observe in Orion will eventually form planetary systems that really resemble our own is far less certain. The high-resolution images show that they are suffering heavy erosion from the outside as well. The energetic radiation and winds given off by the nearby massive young stars are pushing on the gas and dust of the proplyds, shaping them more like wind socks or comet tails streaming away from the source of the blast. The outer layers of the proplyds are stripped, making it doubtful that any planetary systems eventually formed might comprise more than only a core of inner planets tightly wrapped around their host sun.

Planetary Formation

Dust is thus one of the principal ingredients of planetary formation. The nebula originally consists of the tiny ice-covered dust grains each on their own individual orbit around the Sun. Over time they collide and stick with each other to form larger aggregates of particles, eventually growing to form larger condensations of up to a km or so across. By now these will have sufficient mass to start attracting other matter by gravity, and continue to accumulate to form many different planetesimals. The nebula becomes too crowded with such planetesimals, and their number is reduced by further collisions – which either smash the bodies into fragments, or end up combining them into much larger bodies that are the proto-planets. Some of the best evidence we have for this model of planetary formation is to observe snapshots of this process in action, within the dusty debris discs seen around nearby young stars.

Debris discs

Proplyds evolve into flatter, thinner discs formed from the remaining debris shed through these collisions of planetismals within the material encircling the newborn star. They are difficult to study directly because of the proximity to the glare of the young star, but this contrast is reduced when observed in the infrared, or when the light from the star is blocked by an occulting mask. A few nearby examples have been observed in detail. The young star HD15115 is only just slightly brighter than the Sun, and has a debris disc seen edge-on. Its lopsided and misshapen distribution is most likely caused by gravitational disturbances within the disc, perhaps due to the planets bunching and accumulating some of the debris. The way that the infrared light is reflected from such a disc, or that around the 12-million year old star AU Microscopium shows that some of the particles are much larger, and fluffier than typical interstellar dust grains, supporting the idea that they are formed from aggregates of smaller particles. However, we cannot observe the disc close in to the host star – and we are only observing the outer extremities of these discs, well out beyond the equivalent orbit of Neptune.

Formation of Solar System

Our original Solar nebula will have extended out to about ten times further than the orbit of Pluto. The material it contained both thinned out and cooled in temperature with increasing distance away from the proto-Sun at the core of the disc; these changing physical conditions dictated what eventually condensed from the nebula. Closer in to the young Sun, the higher temperature will have caused water and other volatile compounds to have evaporated from the grains. Thus the inner planets are predominately silicate, ie rocky, bodies, formed over a period of several million years. Lighter elements (such as hydrogen and helium) will have been pushed further out into the nebula by the stellar winds (which are strong in young stars). These can then be attracted by gravity to grow a deep atmosphere around a rocky core, developing into large gas giants such as Jupiter and Saturn. Slightly further out, the decreased temperature means that some of the volatile ices such as ammonia, methane and carbon dioxide can be incorporated into Uranus and Neptune. However, at such large radii, the nebula is much less dense and its contents move more slowly; here it takes a lot longer for matter to collide and grow to form the planetismals. So Uranus and Neptune didn’t have sufficient time to grow as large as Jupiter and Saturn before the Sun established itself and its solar wind blew away the surrounding nebula. By the distance of Pluto and the Kuiper Belt, collisions are so rare that only small structures develop.

All the interstellar matter incorporated into the planets and larger moons has undergone significant geological processing over the last few billion years. Only the material retained in the relative deep freeze of space beyond the Kuiper belt of asteroids, in the very distant Oort cloud of comets will still bear some resemblance to the ingredients of the original solar disc, and the interstellar dust it originally contained.

**Interplanetary Dust**

Cometary dust

Although no longer completely pristine, the material released by a comet on its orbit through the inner Solar System may be the closest example we have to original star dust that we are formed from. Certainly it allows us to sample the conditions at the remotest regions of the Solar nebula, way beyond the main planetary orbits. As the comet falls towards the Sun it heats up; fissures and cracks develop on its surface, through which icy material sublimates, dragging out particles of dust along with it. A comet thus leaves a trail of this liberated dust in its wake. At first it forms one of the comet’s two tails (the bluer, straighter tail is due to charged particles), shining by reflected sunlight. Eventually all the dust particles settle into individual orbits around the Sun.

Stardust mission

The *Stardust* spacecraft was launched in 1999 in order to rendezvous with Comet Wild in 2004. It flew directly through the cloud of material emitted by the comet in order to collect some of the dust particles given off. These embedded themselves (at high speed!) in an exposed tray of a very porous substance known as aerogel; this slows down the particles without damaging them, and they bury themselves at the end of a long track that they score in the gel. The tray was then sealed for return to Earth in early 2006, where the captured particles could be examined in the lab. They were found to have a composition very similar to those observed in the outer regions of accretion discs around newly forming stars, and so it appears that cometary dust does resemble true interstellar grains.

Zodiacal light

Any residual dust within our interplanetary medium gradually settles towards the centre of the Solar System. A flattened disc of tiny dust particles lies in the same plane of the planets’ orbits around the Sun, spanning the inner solar system from Mercury to Jupiter. It is sometimes revealed either just before sunrise or just after sunset, when it can scatter sunlight to produce a very faint glow aligned with the direction of the Sun’s apparent path through the sky. This phenomenon is known as the Zodiacal light, and much of the interplanetary dust it is comprised of is highly processed. Although some may be liberated from passing comets, further contributions are produced from rare collisions between asteroids in the asteroid belt.

Micrometeorites

The easiest way to study cosmic dust is perhaps to wait for it to come to you. Every day, the movement of the Earth through the interplanetary medium sweeps up tons of cosmic dust. Many of the particles burn up in the atmosphere to form shooting stars, but if they are small enough – less than 100 microns across – tiny grains can be slowed on impact with the molecules in earth’s atmosphere without melting, and survive their fall to land on the surface as micrometeorites. They can be collected en masse from piled-up surface deposits such as can be found on large polar ice-masses, or encased in ocean floor sediments. Micrometeorites are even collected from the atmosphere, trapped in specially designed plates that travel under the wings of stratospheric-flying NASA aircraft. The smaller of the micrometeorites (less than 50 microns in size) are those thought to originate from cometary ejecta, with the larger being collisional debris from asteroids.

Chondrules in meteorites

A tiny fraction of the larger stony meteorites that fall to the Earth are known as carbonaceous chondrites. Their defining characteristic is the inclusion of small (mm-sized) spherical features called chondrules that originated as (partially) molten droplets in space before being accreted into any parent body. These chondrules contain pristine material that originates from the very outer parts of the solar nebula, which has never been processed as part of any planet or asteroid. Examination of their unusual isotopic chemical composition shows them to be very different from solid matter forming at low temperatures; instead they are thought to have condensed rapidly from stellar matter leaving a star’s envelope, and without dilution with any surrounding interstellar medium. The chondrules include dust grains that originate from other regions of our Galaxy, and which predate the formation of our Solar system.

© Professor Carolin Crawford 2012