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Our Dusty Universe

This thesis examines the detected effects of dust grains in two dissimilar regions at opposite ends of the Milky Way: firstly in explaining anomalous extinction values towards the Galactic bulge through observations of Planetary Nebulae (PNe); and secondly in explaining the apparent photon-dominated regions (PDRs) observed in metal-poor molecular clouds at the Galactic edge. Before recounting my investigations of the role dust plays in just two observed scenarios, I summarise here the broader significance of dust in cosmic processes and our own existence. In fact, we humans are literally made of star dust, which is all the more sobering when one considers that, despite our position in a quiescent part of our Galaxy, we have the temerity to catch a few photons and try to fathom the very processes that brought about our existence.

Today's Universe is indeed dusty, with around one per cent by mass of the interstellar medium (ISM) in the form of dust. However, this was not always the case, as when the first nuclei formed during primordial nucleosynthesis (around t = 100–1000 seconds after the Big Bang, which according to cosmological models based on the Hubble constant and the densities of matter and dark energy, occurred around 13.7 billion years ago), the only stable elements formed, in addition to hydrogen and its isotope deuterium, were helium and lithium. Some time after the last interaction of matter and radiation ($t \sim 3 \times 10^5$ yr), the first stars (and galaxies) formed from this gas. Nuclear fusion reactions in the cores of this first generation of stars synthesised heavy elements (or metals) such as carbon, oxygen and silicon. More massive stars created even heavier elements, all the way up to iron, cobalt and nickel. Successive generations of stars have increased this metallicity to that which can be observed in the local Universe today.

However, compared to our Sun, the relative abundances of metals, i.e. elements heavier than helium, is greatly reduced in the gas phase in the ISM, with elements that can form refractory (heat stable and resistant) solids having the highest depletions. Examples include silicon and oxygen that can form silicates with magnesium and iron; iron particles; silicon carbide, graphite and metal oxides. This suggests that elements that can form refractory solids are removed from the gas phase as solid particles, i.e. dust. In fact, small particles or grains are found in molecular clouds and dark nebulae throughout the ISM. The sizes of dust grains range from $0.001\,\mu$m to $0.1\,\mu$m, and they account for around one per cent of interstellar mass, with a low spatial density of around one grain for every 10^{12} hydrogen atoms, for grains of radius $a \sim 0.1\,\mu$m, where the average H-nuclei density in the ISM, as opposed to clouds, is about one per cubic centimetre (n_{g}, the number density of dust grains is proportional to $a^{-3.5}$, so there are more smaller grains than large). Dust in the ISM is composed primarily of carbon and silicate material, often with mantles of water and ammonia ice or solid CO.

The presence of dust is revealed by dark regions in otherwise rich star fields, e.g. Barnard 86 (Fig. 1.1), where the dust grains heavily extinguish starlight. Dust is also found in circumstellar shells, causing an infrared excess in the spectrum of many stars. In fact, for any line of sight, the existence of dust in the ISM is revealed by the reddening of starlight, where shorter wavelengths are more affected than longer wavelengths. This extinction can be measured by comparing stars of similar mass, temperature and composition (revealed by their spectral signatures), and therefore similar intrinsic luminosity. Differences in detected luminosity can be attributed in part to differences in their distances, but the degree of reddening will indicate the amount of extinction for the respective lines of sight through the ISM.

The observation that, in general, starlight is partially linearly polarised also con-

Figure 1.1: The open star cluster NGC 6520 and the dark nebula Barnard 86 (B86). NGC 6520 consists of young blue stars, possibly just a few million years old, and most likely formed from the molecular cloud B86. Dust from the leftover material in B86 blocks light from other stars that are behind the cloud. The background of the image is the central bulge of the Milky Way. Credits: Fred Calvert, Adam Block, NOAO/AURA/KPNO/NSF.

firms that dust grains cause interstellar extinction, where the amount of polarisation appears to be proportional to the amount of extinction. For this to be so, isotropic interstellar grains must be non-spherical and there must be some degree of alignment of these elongated grains, so that radiation with electric vectors parallel to the grain's longer axis will be more extinguished than vectors parallel to the short axis. Aligned grains of anisotropic material, such as graphite, may also cause polarisation. Dust grains will normally be rotating (angular frequency $\omega \sim 10^5$ Hz), and if they are paramagnetic and a magnetic field exists in the interstellar gas, this will tend to align the grain's axis of rotation with the magnetic field, although this will counteracted by collisions, which will randomise the spin axis of a grain.

Dust grains also reveal their existence by scattering starlight, thereby filling the Galaxy with diffuse light, which can be directly observed as a reflection nebula, such as

Figure 1.2: IC 349 or Barnard's Merope Nebula illuminated by strong radiation from the nearby hot bright star Merope, located in the Pleiades star cluster. Credits: NASA and The Hubble Heritage Team (STScI/AURA).

in the Pleiades (Fig. 1.2), or as reflected light from shells of dust that are ejected during the latter phases of a star's evolution, such as V838 Monocerotis (Fig. 1.3). Dust particles also cause several strong infrared absorption lines in the light from background stars. Examples include the Si–O stretching and bending modes in amorphous silicates at 9.7 and 18 μm respectively, the O–H stretching mode in amorphous H_2O ice at 3 μm, and the vibrational excitation of CO ice at 4.7 μm, as well as various hydrocarbon C–H stretching modes between 3.3–11.3 μm.

Timescales for dust formation by condensation within interstellar clouds are very long ($> 10^9$ yr), so denser regions with shorter timescales are required. Outflowing gas from cool stars provide the initial densities ($n \sim 10^{13}$ cm^{-3}) and temperatures ($\sim 10^3$ K) for particles to nucleate and settle out, as the cooling gas is blown clear into the ISM (see section 2.2 on how the formation of planetary nebulae returns stellar material to the ISM). The type of particles that form is sensitive to the cosmic abundance of the elements, with successive generations of stars increasing the metallicity of a given locality within a galaxy, e.g. the central bulge region of our Galaxy has likely seen far more star formation than regions at the periphery of the Milky Way. For temperatures of 1000–2000 K carbon monoxide is stable, such that most of the C and O atoms are bound in this form. However, many stars are either oxygen- or carbon-rich, resulting in the preferential formation of dust particles that are either oxides or solid carbon grains. Grains may grow further by accretion of atoms and molecules from the ISM, although, as mentioned above, timescales are likely to be unacceptably long unless the gas density $n \geq 10^3\,\mathrm{cm}^{-3}$, which is the case in cold molecular clouds.

If dust grains have icy mantles, these will evaporate if the grains are heated sufficiently, for example when a clump of denser gas in a molecular cloud contracts to form a prestellar core. Refractory materials such as hydrocarbons, graphite or silicates are very durable, as evidenced by the presence of rocky planets and even ourselves in the Solar System. However, sputtering by high-speed atoms can knock lattice atoms out of a grain and lead to its eventual destruction. Energetic supernovae ($\sim 10^{43}$ J) can set up shocks that disrupt the ISM and either destroy or reduce the size of dust grains.

Dust grains also play a role in the evolution of interstellar gas clouds. Depending on their energy (4–14 eV), ultraviolet (UV) photons can heat either the gas or dust in a molecular cloud. For UV (or visible light) photons with an energy less than the work function of a typical dust grain ($W \sim 5$ eV), the radiation is absorbed by the grain, and then re-emitted in the infrared. As grains are not perfect radiators they achieve a temperature above the microwave background (2.7 K) of between 14–45 K, depending on the material. Higher energy UV photons eject electrons from grains via the photoelectric effect, where each released electron will carry several eV of energy, which will heat the gas via subsequent collisions. Dust can also act as a sink for energy, when higher temperature atoms or molecules (e.g. at 100 K) stick to lower temperature grains, where the energy difference is lost from the gas, and the grain subsequently radiates the energy away.

For star formation to occur in molecular clouds, there has to be a mechanism for removing the additional kinetic energy that is converted from gravitational potential energy when denser clumps in a cloud undergo collapse. As explained in more detail in section 8.2, various molecular species, particularly CO, radiate effectively via collisional excitations, thereby cooling the cloud. However, the formation of molecules in the first place, even H_2 the most common, are difficult to explain with just gas phase reactions. Two body atomic collisions offer little opportunity for radiative stabilisation, with around only one in 10^5 collisions producing a molecule. Interstellar densities make the possibility of a third body, that could remove some energy, even more unlikely. Added to this, UV photodissociation and various chemical reactions effectively destroy molecules on short timescales (~300 yr), although it should be noted that once enough basic molecules exist (and are replenished), more complex species can form through chemical reactions.

It is self-evident that a mechanism for molecular formation does exist, as dense clouds consist primarily of molecular hydrogen, as well as over 100 other molecules. The surface of dust grains are believed to be the sites where H_2 can form, with the minimum requirement that one H atom is retained at the surface long enough for a second H atom to arrive and locate the first. In the vicinity of a grain, long-range van der Waals forces between an H atom and all the atoms of the grain create a potential well for the infalling H atom, which on collision becomes bound to the surface, due to some energy being transferred to the grain lattice. The atom may then move laterally across the surface before becoming bound at a particular site in the lattice. Subsequent movement to other bound lattice sites is achieved by the quantum-mechanical penetration of the barrier between sites. Simple calculations indicate that an H atom can be retained long enough at a grain's surface for a second atom to arrive and be met by the first atom. Upon formation H_2 is ejected from the grain, due to the large amount of energy released when the two H atoms combine. For other atoms and radicals, binding energies for grain surfaces are larger than for hydrogen, so if this catalysis works for H, it is likely to work for other molecules such as H_2O, CH_4 and NH_3. In denser regions ice mantles can also form on dust grains via two different processes. Water ice most likely forms when free oxygen atoms arriving at a grain surface successively combine with H atoms, forming H_2O molecules that are mostly retained. In this scenario, it is likely that the H atoms arrive at the grain's surface after the O atom, since two H atoms on the surface will find one another, react and desorb as H_2 before an O atom arrives. In contrast, solid CO forms by means of simple freeze-out on the cold dust.

Much fuller treatments on the role of dust in the ISM can be found in Dyson and Williams (1997), Evans (1994), Millar and Williams (1993) and Whittet (1992). Interstellar extinction and alternative methods of measurement are discussed in more detail in chapter 5.

In the first part of this thesis I examine the detected effects of dust grains in explaining anomalous extinction values towards the Galactic bulge through observations of Planetary Nebulae (PNe). Angular diameters, fluxes and extinction of compact PNe are derived from observations, providing evidence for steeper extinction towards the Bulge. I suggest that for the inner Galaxy the low-density warm ionized medium is the site of the anomalous extinction, and that low values of extinction can also be derived using appropriate dust models. I then go on to investigate the detected effects of dust grains in explaining the apparent photon-dominated regions (PDRs) that I have observed in metal-poor molecular clouds at the Galactic edge. I present observations of Edge Clouds 1 and 2 (EC1 & EC2), and these are used to determine their physical characteristics. Chemical models are used to reproduce the abundances in EC2 and they indicate: heavy elements may be reduced by a factor of five relative to the solar neighbourhood; very low extinction due to a high gas to dust ratio; an enhanced cosmic ray ionisation rate; and a high UV field compared to local interstellar values. Although these two regions, at opposite ends of the Milky Way, appear quite dissimilar, I will show that the existence of small dust grains, probably caused by supernova shocks, play a key role in determining the nature of these two environments.

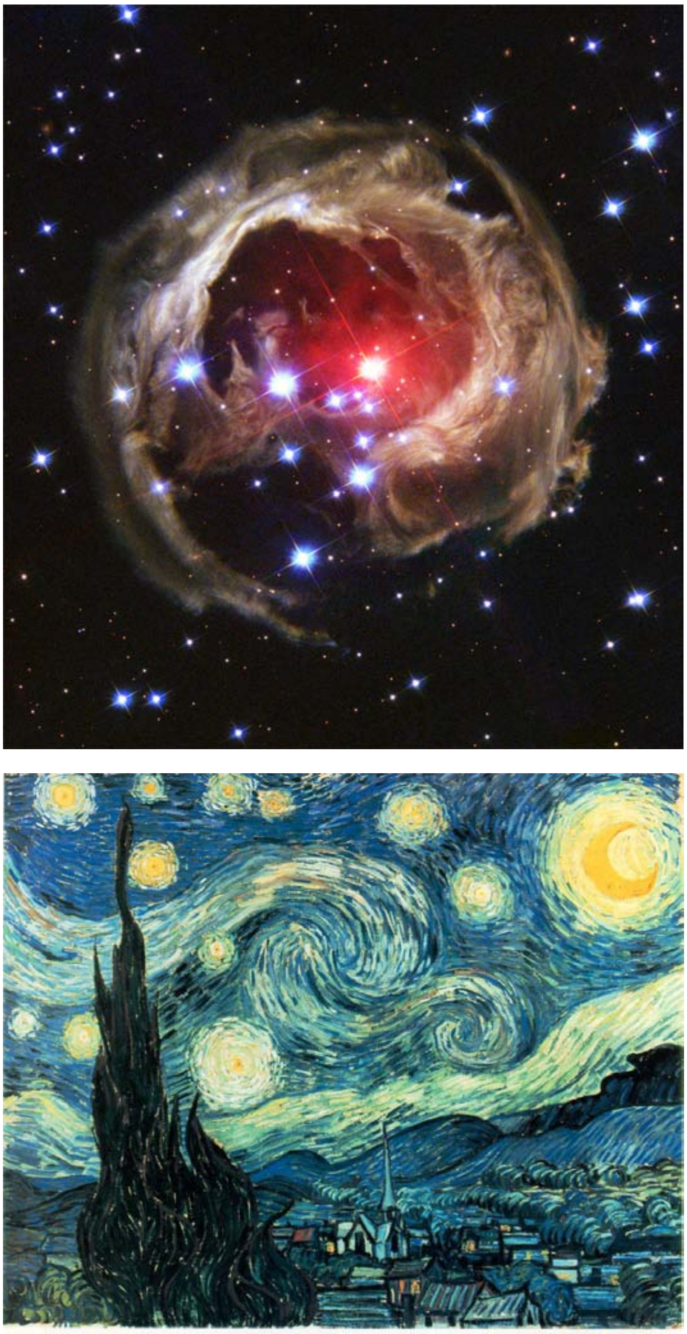

Figure 1.3: Expanding halo of light around V838 Monocerotis. The illumination of interstellar dust comes from the red supergiant star at the middle of the image, which gave off a pulse of light two years before the image was taken. Interestingly, the image resembles Van Gogh's painting (also shown) *The Starry Night* (Saint Rémy, June 1889, oil on canvas), which is in the collection of the Museum of Modern Art in New York. Credits: NASA, the Hubble Heritage Team (AURA/STScI) and ESA.