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Space-borne observations of the life cycle of interstellar gas and dust

The gas and dust in the interstellar medium (ISM) form an essential part of the evolution of galaxies, the formation of stars and planetary systems, and the synthesis of organic molecules that may lead to the emergence of life elsewhere in the Universe. Over their lifetimes, stars return much of their mass to the ISM through winds and supernova explosions, leading to a slow enrichment in heavy elements and dust that form the building blocks from which future generations of stars and planets are made. Stars also inject energy into the ISM via ultraviolet photons, shocks, and wind-blown stellar bubbles. Cosmic rays, x-rays, and ionizing photons influence the ionization state of the gas, whereas shielding by gas and dust leads to the cold, neutral phases of the ISM where molecules can flourish. As a result, the composition and structure of the ISM is governed by a complex interplay of microscopic and macroscopic processes. Understanding this life cycle of gas and dust in the ISM is a key problem in astrophysics, for understanding not only our own Galaxy but also the much more rapid cycling between the ISM and stars in the earliest star-forming galaxies in the Universe (Figure 1).

Research on the ISM started early in the twentieth century with the ground-based detection of interstellar Na and Ca^+ optical absorption lines (Hartmann 1904, Heger 1919) and the appearance of many dark regions on photographic surveys of the Milky Way (e.g., Barnard 1919). Definite evidence for the presence of interstellar dust came from observations by Trumpler (1930), whereas the first interstellar molecules, CH, CH^+, and CN, were identified between 1937 and 1941 (Swings and Rosenfeld 1937, McKellar 1940, Douglas and Herzberg 1941). Around the same time were detected the diffuse interstellar bands (DIBs; Heger 1922, Merrill 1934), whose identification is still uncertain after more than 75 years. Initially, inspired by the identification of simple diatomic species in the ISM, these bands were attributed to molecular absorbers. However, once interstellar dust was established as an important interstellar component, an origin for the DIBs in absorption by dust grains was taken for granted. Nowadays the pendulum has swung back – and for good reason – to molecules as the prime candidates for the carriers of these absorption features (Snow 1995). The foundation of the theoretical study of the ISM and the physical conditions that may prevail there was put forward by Arthur Eddington (1926) in his famous Bakerian Lecture. It was also he who exclaimed that "atoms are physics but molecules are chemistry" with the scarcely hidden message that astronomers should stay away from molecules. Nowadays, despite Eddington's warning, molecular astrophysics is a thriving field driven to a large extent by the wealth of molecular data that has become available over the last three decades, much of it harvested from space.

With the detection of the 21 cm H I line by Ewen and Purcell (1951), the study of the ISM turned to ground-based radio observations, and data thus gathered still provide a wealth of information on the distribution and kinematics of the neutral, atomic ISM in our Galaxy and other galaxies (e.g., Hartmann and Burton 1997). The detection of the first molecules at radio wavelengths (Weinreb *et al*. 1963, Cheung *et al*. 1968) paved the way for the development of millimeter and submillimeter wave astronomy. The ubiquitous CO molecule was detected by Wilson *et al*. (1970), and a surprisingly large number of other molecules have since been found in dense molecular clouds (see van Dishoeck and Hogerheijde (1999) for a recent overview).

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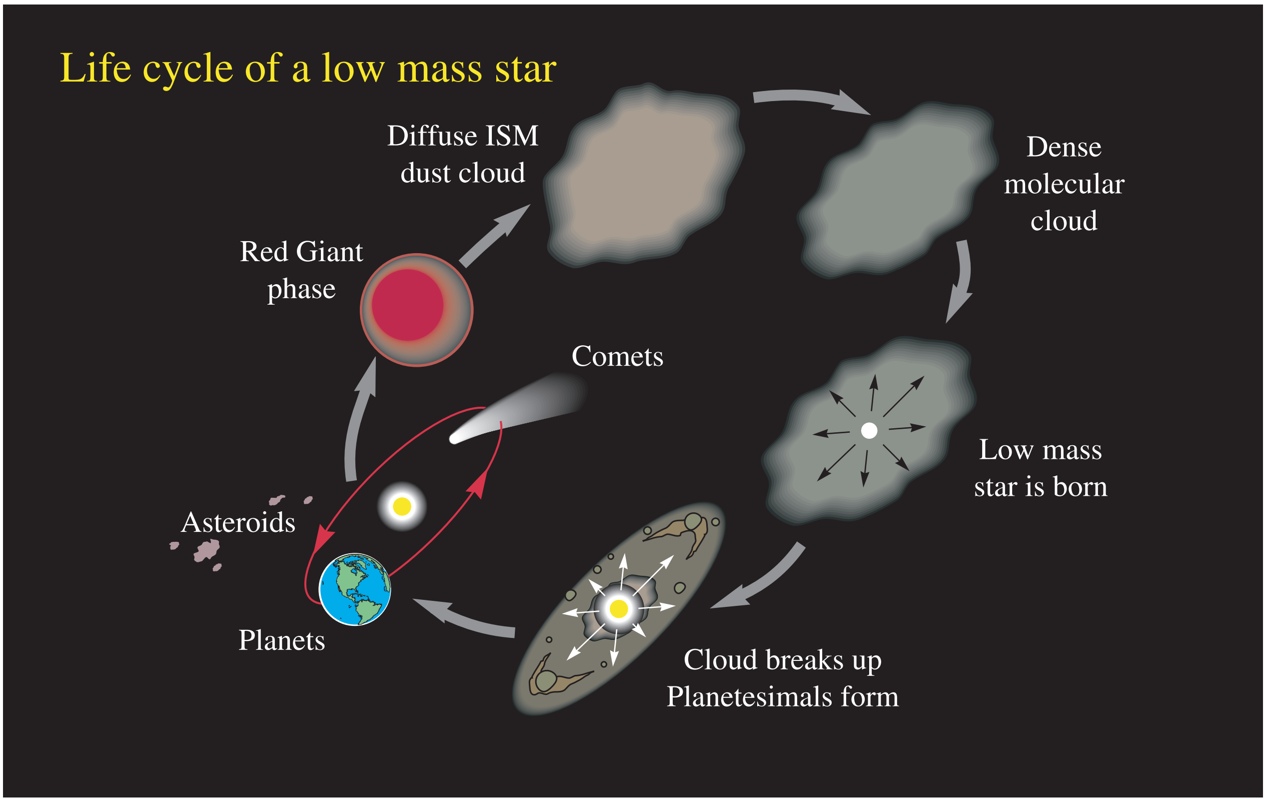

Figure 1 Schematic diagram of the lifecycle of dust and gas from the diffuse ISM, through star formation, to the late stages of stellar evolution. (Pendleton and Cruikshank 1994.)

Space-based ultraviolet observations of the neutral ISM started with small spectrometers flown on rockets, which led to the important detection of H_2 by Carruthers (1970). The later Copernicus satellite (Spitzer and Jenkins 1975) provided extensive new information on H_2 and other interstellar lines, mostly of atoms in various ionization stages. Together with the ground-based H I data, they stimulated the development of the two- and three-phase model of the ISM in which the gas is heated by the action of the photoelectric effect on grains and by large-scale supernova explosions, and is cooled by line radiation from atoms (Field *et al*. 1969, McKee and Ostriker 1977).

Because the typical temperatures of the cold, neutral ISM range from ~ 10 to a few hundred K, most of the thermal emission occurs at mid- and far-infrared wavelengths, a part of the spectrum which is largely inaccessible from the ground. It is therefore not surprising that much of our progress over the last 30 years or so has come from space-based observations in the infrared. To our knowledge, the earliest discussion of the importance of the infrared for the study of the ISM goes back to an exchange between Spitzer, Kahn, and Drake at the 3rd Symposium on Cosmical Gas Dynamics (Burges and Thomas 1958). Of course, the first detection of infrared radiation – from the Sun – was by William Herschel in 1800, while his son John Herschel was the first to measure the total power emitted by the Sun, in 1838, and Edward Stone that of stars, in 1869–70 (Harwit 1999). In the late 1870s Thomas Edison observed Arcturus and the solar corona in the infrared from a chicken coop in order to win a bet (Eddy 1972). However, despite these early successes the field of infrared astronomy lay dormant until the late 1960s to early 1970s, when progress in infrared instrumentation truly opened the infrared window of the spectrum.

The 1958 discussion mentioned above went on to consider the observational difficulties of detecting a low-intensity astronomical signal against a 300 K telluric background and emphasized the advantage of balloon or satellite observations. This was elaborated upon in an early discussion of infrared radiation from interstellar grains by Stein (1967), who concluded that it was hopeless even to consider observing it through the mid-infrared telluric windows. Fortunately he was not much impressed with his own pessimistic prediction, and, together with (among others) Fred Gillett, he went on to pioneer the field of mid-infrared spectroscopy of interstellar dust using a circular variable filter-wheel. By the early 1970s it was fully appreciated that the best way to determine the composition of interstellar

Table 1 Selected infrared space missions and instruments relevant to ISM research

Mission	Instrument	Acronym	Wavelength range (μm)	Resolving power	Operational period
IRAS	Photometers		12, 25, 60, 100	3–5	1983
	Low Resolution Spectrometer	LRS	7.7–22.6	20–60	
COBE	Far-InfraRed Absolute Spectrophotometer	FIRAS	100–10 000	100–500	1989–1993
IRTS	Far Infrared Line Mapper	FILM	63, 158	400	1995
ISO	Short Wavelength Spectrometer	SWS	2.5–45	2000, 20 000	1995–1998
	Long Wavelength Spectrometer	LWS	43–197	200, 10 000	
	Camera	CAM	2.5–17	3–20	
	Camera+Circular Variable Filter	CAM-CVF	2.3–16.5	35–50	
	Photometer	PHT	3.3–200	3	
	Photometer-Spectrometer	PHT-S	2.5–5, 6–12	90	
SWAS	Heterodyne Instrument		545, 610	5×10^5	1999–

dust was through infrared spectroscopy (Gaustad 1971). That was an impressive foresight and insight, as well as a change of direction in a short time. It should be remembered that by the late 1960s and early 1970s, rocket-borne ultraviolet studies had revealed the ubiquitous presence of 2200 Å bump in the interstellar extinction curve (Stecher 1965, Bless and Savage 1972), which had been successfully modeled in terms of small graphite grains (Gilra 1972).

Yet, as has become abundantly clear since then, advances in our knowledge of the physics and composition of the dust and gas have followed advances in infrared detector and heterodyne submillimeter receiver technology, and the development of airborne and space-based platforms through pioneers such as Martin Harwit, Gerard Kuiper, Frank J. Low, Charles H. Townes, and many others (e.g., Harwit *et al*. 1966, Kleinmann and Low 1967). The Lear Jet and the Kuiper Airborne Observatory (KAO) in the USA, and the US–Netherlands–UK Infrared Astronomical Satellite (IRAS), have been pivotal in developing the field, which has culminated with ESA's recent Infrared Space Observatory (ISO) (Table 1). Other important missions include NASA's Cosmic Background Explorer (COBE), balloons, rockets, the Japanese Infrared Telescope in Space (IRTS), the US Air Force project Midcourse Space Experiment (MSX), and NASA's Submillimeter Wave Astronomical Satellite (SWAS). In this respect, the future looks very promising, with the Space Infra Red Telescope Facility (SIRTF), the ASTRO-F mission, the Herschel Space Observatory (formerly known as FIRST), and the Next Generation Space Telescope (NGST) all on the horizon.

This chapter presents an overview of the air- and space-borne observations that over the last 30 years have played a crucial role in our understanding of the cold and dense neutral ISM and the formation of stars. The various phases of the ISM considered here are summarized in Figure 2, and are discussed in order from the diffuse medium to old stars. The richness of the infrared wavelength region is illustrated in Figure 3, which shows the complete ISO Short Wavelength Spectrometer (SWS) spectrum of Orion centered at the IRc2 source (van Dishoeck *et al*. 1998). Its proximity and extraordinary brightness have made this source the prime target for most of the pioneering observations at infrared wavelengths (e.g., Genzel and Stutzki 1989). Much of the complexity is the result of the disruption of the star-forming environment by powerful outflows from the massive young star, and its intense ultraviolet radiation dissociating and ionizing the gas on the cloud surfaces. Orion is the nearest and best studied region of massive star formation in the Galaxy, and therefore also serves as a template for more distant star-forming regions in other galaxies. The strong continuum is due to thermal emission from warm dust (50–300 K) and peaks around 70 μm. A wealth of superposed lines of atoms, ions, and molecules is seen, which can be used to constrain the physical parameters (see Figure 8 of Genzel 1992) and assess the relative importance of different processes, in particular shocks *v*. ultraviolet radiation.

Space limitations preclude a comprehensive review of the field, and only topics in which space-based observations have played a crucial role are covered. For example, ground-based submillimeter observations of molecular clouds are not mentioned, but the composition of ices in such clouds, as deduced from mid-infrared spectroscopy is. Ultraviolet observations of the atomic component of the ISM and space-based data on ionized H II regions and continuum observations of young stars are discussed elsewhere in this volume. Each section starts with a brief historical review and an introduction of the basic physics, and goes on to

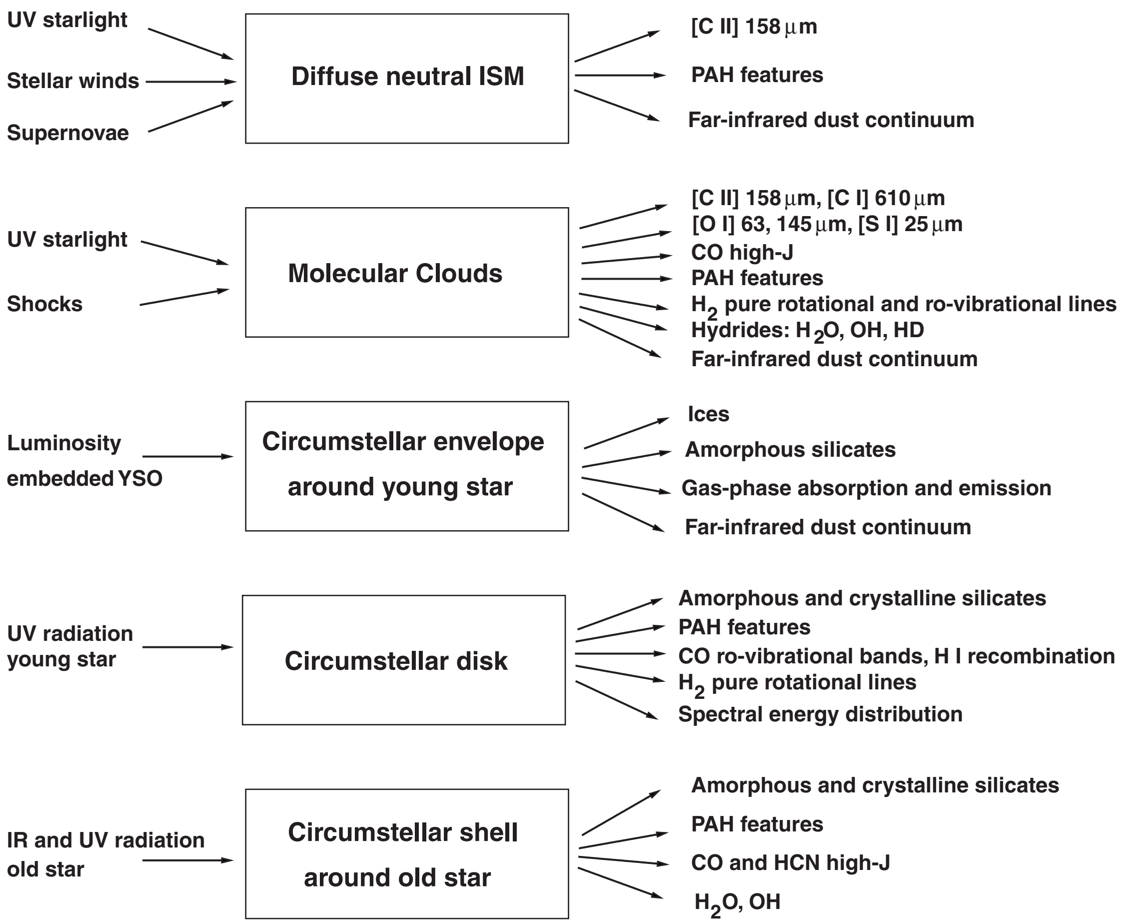

Figure 2 Schematic diagram of the energy input to the various phases of the ISM discussed here, and the resulting diagnostic lines at mid- and far-infrared wavelengths. Most of these features can only be observed from air- and space-borne platforms. *PAH* stands for polycyclic aromatic hydrocarbons or large carbonaceous molecules in general; YSO for young stellar objects.

focus on recent ISO results to illustrate the current state of knowledge, in particular the spectroscopic data obtained with the ISO's Short Wavelength Spectrometer (SWS, 2.4–45 μm) and Long Wavelength Spectrometer (LWS, 43–197 μm) (see Table 1 for an overview). Excellent previous summaries include the proceedings of the *Airborne Astronomy Symposium* (Haas *et al*. 1995), which also contains many photographs of key people in the field, and the proceedings of the *The Diffuse Infrared Radiation and the IRTS* (Okuda *et al*. 1997). Further details of ISO results are contained in *Star Formation with the ISO Satellite* (Yun and Liseau 1998), *ISO's View on Stellar Evolution* (Waters *et al*. 1998), *Analytical Spectroscopy with ISO* (Heras *et al*. 1997, 2000), *Solid Interstellar Matter: The ISO Revolution* (d'Hendecourt *et al*. 1999a), and *The Universe as seen by ISO* (Cox and Kessler 1999). Reviews of various aspects of the neutral ISM include Spitzer (1978), Habing (1988), Genzel (1992), and Hollenbach and Tielens (1999). Recent reviews of astrochemistry can be found in *The Molecular Astrophysics of Stars and Galaxies* (Hartquist and Williams 1998), van Dishoeck and Blake (1998), van Dishoeck and Hogerheijde (1999), Langer *et al*. (2000), Ehrenfreund and Charnley (2000), and the proceedings of IAU Symposium 197 on *Astrochemistry: From Molecular Clouds to Planetary Systems* (Minh and van Dishoeck 2000). Interstellar dust has been reviewed by, for example, Tielens and Allamandola (1987a,b), Whittet (1992), and Cox *et al*. (2000).

1 THE DIFFUSE INTERSTELLAR MEDIUM

1.1 Very small grains

The infrared emission from dust in the diffuse, neutral ISM is faint and extended, and observations have been mostly limited to what is possible with cooled telescopes in space. The all-sky maps by IRAS (at 12, 25, 60 and 100 μm) and

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