THIRD EDITION

The Physics of the Interstellar Medium

J. E. Dyson
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CRC Press
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Front cover image: *The image was made by NASA's Spitzer Space Telescope operating in four wavebands in the infrared, between 3.6 and 8.0 micrometres, and shows star formation occurring in a dense globule of gas that is embedded in high pressure ionized gas surrounding a massive star to the left of the globule (not shown in this image). The star also has a powerful wind that together with the ionized gas compresses the globule, making a dense rim. The wind creates a long tail. Two young stars have been created within the dense gas in the head of the globule. Their winds have swept a spherical cavity in the gas of the globule.* Credit: NASA/JPL-Caltech/W. Reach (SSC/Caltech)

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Contents

Preface to the Third Edition

Our knowledge of the interstellar medium in the Milky Way galaxy – and in many external galaxies – has increased enormously since John Dyson and I wrote the first edition of this book, published in 1980. Our understanding of the importance of this tenuous component in driving the evolution of all galaxies has developed very substantially since the second edition was published in 1997. However, the main purpose of this book remains unchanged: we seek to illustrate many interesting aspects of physics by describing some unfamiliar situations that arise in interstellar space. This third edition of the book is aimed primarily at undergraduates on physics courses, as were the earlier editions. Although the book does not give a comprehensive coverage of the interstellar medium, it has nevertheless also been used by other readers as a concise introduction to the study of the interstellar medium, and I hope that the new edition will also be useful for this purpose.

Perhaps the most important area in which studies of the interstellar medium have developed is in our understanding of the formation of stars and planets occurring within very dense and dusty regions of the interstellar medium. This work depends to a large extent on the detection of emissions from molecules and dust within the dense interstellar gas. Infrared emissions from dust and molecules are not only important tracers of the gas in regions that are opaque to optical radiation, but they also are significant players in controlling the physical conditions and evolution of gas in star-forming regions. In this third edition, more prominence is given to the interstellar chemistry that generates interstellar molecules, to the properties of interstellar dust, and to the grand narrative that describes current ideas on how the formation of stars and planets occurs in the interstellar medium.

The original structure of the book is retained in this third edition, and the intellectual level required by a reader and the aim to present brief, simple explanations in a short book are maintained as in earlier editions. The opportunity is taken to include some recent astronomical images within the chapter texts, where appropriate. I am grateful for advice on some aspects of the revision from friends and colleagues, especially Cesare Cecchi-Pestellini and Serena Viti, but all errors and omissions are mine.

David A Williams

Some Relevant Physical and Astronomical Information

ENERGY CONVERSION TABLE

	Joule	Electron volt	Kelvin
Joule	–	6.2414×10^{18}	7.2430×10^{22}
Electron volt	1.6022×10^{-19}	–	1.1605×10^{4}
Kelvin	1.3806×10^{-23}	8.6173×10^{-5}	–

SOME USEFUL PHYSICAL CONSTANTS

Velocity of light, c	2.9979×10^{8} m s^{-1}
Gravitational constant, G	6.6743×10^{-11} m^3 kg^{-1} s^{-2}
Planck constant, h	6.6261×10^{-34} J s
Dirac constant, $\hbar = h/2\pi$	1.05457×10^{-34} J s
Electron charge, e	1.60218×10^{-19} C
Electron rest mass, m_e	9.10938×10^{-31} kg
Proton rest mass, m_p	1.67262×10^{-27} kg
Boltzmann constant, k	1.38065×10^{-23} J K^{-1}
Avogadro number, N_A	6.02214×10^{23} mol^{-1}
Bohr radius, a_0	0.529177×10^{-10} m
Permittivity of free space, ε_0	8.85419×10^{-12} C^2 N^{-1} m^{-2}

ASTRONOMICAL DATA

Time and distance measurements

I year	3.1557×10^{7} s
1 light year (ly)	9.461×10^{15} m
1 parsec (pc)	3.086×10^{16} m = 3.26 ly

Solar data

Mean distance from Earth, 1 astronomical unit (1 au) = 1.496×10^8 km = 8.3 light minutes.

Solar mass	1.989×10^{30} kg
Solar radius	6.957×10^8 m
Solar mean density	1408 kg m^{-3}
Solar age	4.6×10^9 yr
Solar energy emission rate	3.828×10^{26} J s^{-1}

Milky Way galaxy data

Diameter	~30 kpc
Mass	~10^{12} solar masses
Radius at the Sun	~8 kpc
Rotation period at the Sun	2.4×10^8 yr
Age of the Milky Way galaxy	1.2×10^{10} yr

Stellar Classifications

Very occasionally in this book we refer to a type of star using a conventional classification system. The system is based on lines that are observed in the stellar spectrum which are used to determine the effective temperature and other properties of the star. Stars are arranged in classes O, B, A, F, G, K, and M, where O stars are the hottest (effective temperatures greater than about 30 000 K) and M stars are coolest (around 2400–3700 K). The Sun is a G star (temperature 5200–6000 K). These broad classes are subdivided by a number running from 0 (hottest) to 9 (coolest), so for example, the Sun is a G2 star. There are several other descriptors that refer to luminosity, evolutionary state, and spectral peculiarities.

Authors

John Dyson made outstanding research contributions over many years to our understanding of the responses of interstellar media to winds from stars and from active galaxies. He had a huge influence on these subjects and his work gained an international reputation. Much of his career was at the University of Manchester where he became Professor of Astronomy and Head of Astrophysics. He moved in 1996 to the University of Leeds, becoming Dean of Research, and was appointed Emeritus Research Professor in 2006.

He died in 2010 and is much missed by friends and colleagues world-wide who valued his scientific insight, quick wit, kindness and generosity.

David Williams is currently Emeritus Perren Professor of Astronomy at University College London. While at NASA's Goddard Space Flight Center in the 1960s he became interested in interstellar molecules and interstellar dust as potential probes of the interstellar medium. When John Dyson and David were both working in Manchester, John emphasised the importance of cosmic gas dynamics in understanding interstellar chemistry and dust, and David built a research group at UMIST to investigate these and other topics. He left Manchester in 1994 for UCL and has continued to study problems in interstellar physics and chemistry.

1 Introduction

1.1 GALAXIES AND THE GALAXY

If we are fortunate enough to see the sky on a moonless and cloudless night, then, when our eyes have become accustomed to the dark, we can discern the prominent feature called the Milky Way. This is a band across the sky containing a large number of bright stars and a background of many fainter stars – so many, in fact, that our eyes cannot resolve them and we see their light as a diffuse (i.e. 'milky') luminosity. This band of stars appears across the sky because the Sun is one of a vast collection of stars, most of which are arranged in the shape of a disc. When we look in the plane of the disc, we see many stars; when we look out of the plane, we see fewer stars. This collection of stars – most of them in the plane of the disc and some out of the plane in a spherical region – is called the Milky Way galaxy. The Milky Way is only one galaxy among an enormous number of galaxies.

The shape and extent of a galaxy, seen with the eye or a telescope, are defined by the stars it contains. This book, however, is concerned with material in the Milky Way galaxy, material that our eyes do not easily see but which, nevertheless, is present and which plays an essential role in the evolution of the galaxy. This material is the *interstellar medium*. In this book, we'll describe some of the interesting applications of physics to the study of the interstellar medium of the Milky Way galaxy, and at the same time, we'll try to explore the fundamental role it plays. However, this is a book about the *physics* of the interstellar medium in the Milky Way and should be read as a simple account of some applications of physics. It isn't a comprehensive description of all aspects of the interstellar medium of the Milky Way galaxy.

Before we come to describe evidence for the existence of material in the space between the stars, we should first have some idea of the dimensions of the galaxy. Our Sun appears to be a fairly typical star of the Milky Way galaxy, which is estimated to contain about 10^{11} stars. The Sun is not located in any special position in the galaxy, such as the galactic centre, but is in the plane of the disc about two-thirds of the galactic radius from the galactic centre. We cannot see, either by eye or by optical telescope, more than a mere fraction of the galaxy, because the intensity of visible light is diminished by a general extinction as the light travels in the plane of the galaxy. Out-of-plane directions are less extinguished. We shall have more to say about that interstellar extinction, but it was the first sign that the interstellar medium wasn't empty: evidently, it contains something that absorbs and scatters starlight. However, as we shall see, the galaxy can be investigated by other means, and we know that its many stars are distributed over a large volume. The diameter of the disc is of the order of 30 kpc (or about 100 thousand light years), and its thickness is about 2 kpc (or about 6 thousand light years). Stars are therefore about 10 light years from their nearest neighbours, on average, though the distribution of stars in space is far from uniform. Obviously, stars are very small compared with these dimensions, so that essentially all the vast space inside the galactic volume is occupied by the interstellar medium, which – as we'll describe – is a non-uniformly distributed dusty gas. The whole galaxy is gravitationally bound; it has spiral structure within it, and it rotates. The shape and structure of the Milky Way galaxy are thought to be similar to those of some external galaxies, and an image of a galaxy believed to be similar to the Milky Way is shown in Figure 1.1.

FIGURE 1.1 Image of spiral galaxy M74. This galaxy is seen by face-on by observers on Earth. It is about 10 Mpc distant, contains about 10^{11} stars, is slightly smaller than the Milky Way, and shares similar spiral structure. The arms contain many bright blue stars and regions of red emission from ionized hydrogen. (Image credit: NASA, ESA, and the Hubble Heritage (STSC/AURA)-ESA/Hubble Collaboration; Acknowledgment: R Chandar (University of Toledo) and J Miller (University of Michigan).)

The Milky Way galaxy is merely one of an enormous number, perhaps $\sim 10^{11}$, of galaxies in the Universe, and the dimensions of the visible Universe are about a factor of about 10^5 larger than those of the Galaxy. We can sometimes investigate the properties of our own Galaxy by studying other galaxies that we can see more readily. The distant galaxies appear to be receding from our own Galaxy, with velocities increasing (and apparently accelerating) with distance. Distances between neighbouring galaxies are very much greater than the dimensions of galaxies themselves, and are typically measured in Mpc (or millions of light years). Therefore, the light gathered by our telescopes and focused to form an image of distant galaxies must have been travelling on its journey long before human beings evolved on Earth. The space between the galaxies – intergalactic space – is not our concern in this book, but, in passing, we note that any gas in intergalactic space must be much less dense than the gas in interstellar space. Studies show that galaxies exist in various forms. Some are irregular, some show a more well-defined disc shape, while some of these have spiral structure (spiral arms) within them. Some are classified as elliptical. Our own Galaxy is known to have spiral structure similar to M74. Figure 1.2 shows photographs of several types of galaxy. All galaxies have interstellar matter; they may be poorer or richer in interstellar matter than the Milky Way. Our discussion in this book is directed towards interstellar matter in the Milky Way galaxy, but the ideas expressed have general application to interstellar matter in all galaxies.

When we look at the sky, it is obvious that some stars appear much brighter than others. This is often because such stars are relatively nearby, but some stars appear bright because they are intrinsically powerful sources of radiation. Astronomers can, by a variety of means, deduce the masses and intrinsic luminosities of stars, and these results agree well with theories of stellar evolution. These theories tell us that stars have masses within a range of about 0.1 to about 100 times the mass of the Sun ($M_\odot$), and that luminosities corresponding to these masses may range from about 10^{-3} to 10^6 times the luminosity of the Sun. The more massive the star, the greater is its luminosity. Therefore, the brightest stars, containing nearly 100 times the amount of fuel as the Sun, are squandering it at a rate 10^6 times faster. We therefore expect that they can exist only for 10^{-4} times the life of the Sun, that is, for about a few million years. This seems a long time for us on Earth, but for the galaxy, these bright stars are transient objects, like candles which soon burn down. We are forced to conclude that such stars have formed in the recent past, and – by implication – that they are certainly forming now. The galaxy *evolves*; it was not formed in the state in which we see it now.

At the end of its life, a sufficiently massive star explodes violently in a dramatic event called a supernova. These explosions are so powerful that we can observe their effects even when they occur in distant galaxies; the exploding star may become (very briefly) as bright as its host galaxy. The last one known to occur in the Milky Way occurred more than 300 years ago, but on average the Milky Way may be host to two supernovae per century. Perhaps the most famous supernova that occurred in our own galaxy is the one that was observed in 1054 AD, and which caused the Crab nebula, an extended supernova remnant

(a) (b) (c) (d)

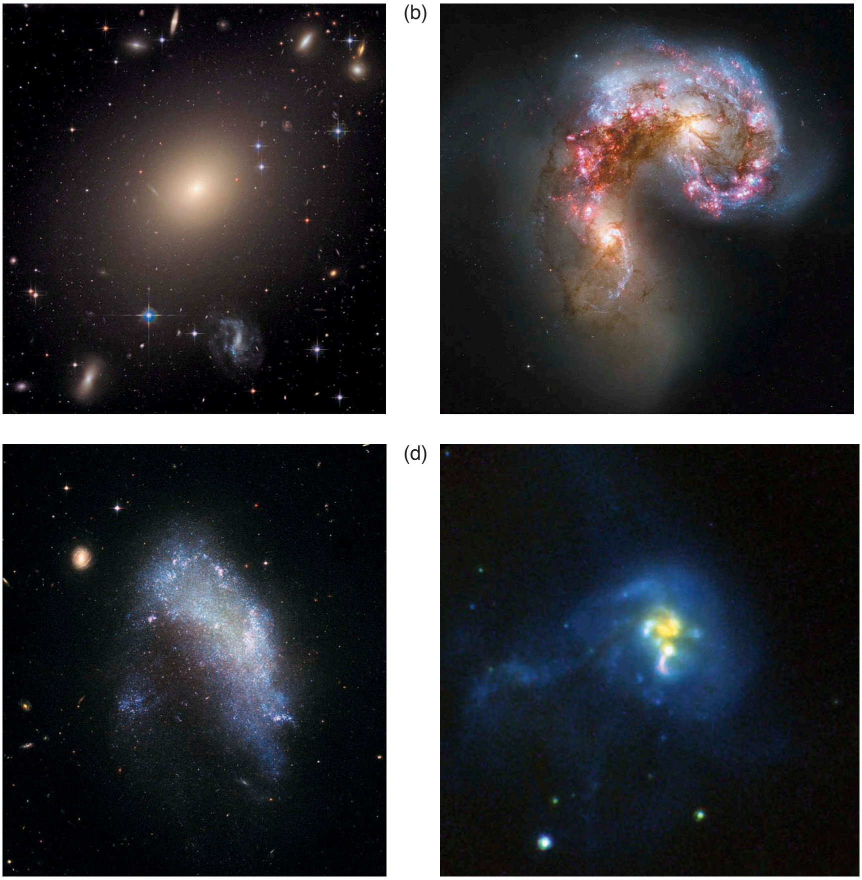

FIGURE 1.2 Variety in galaxies. (a) Elliptical galaxies, of which ESO 325-G004 is one example, have a smooth profile and an ellipsoidal shape. They have relatively few high-mass bright stars and consist mainly of low mass stars. (Credit: NASA, ESA, and The Hubble Heritage team and J Blakeslee.) (b) Starburst galaxies have a very high rate of star formation which can be stimulated by a close collision between galaxies. This is the case for the Antenna Galaxies, a merger between two galaxies – NGC 4038 and 4039. (Credit: ESA/Hubble and NASA.) (c) Irregular galaxies are often small and their shapes are a result of near collisions with other massive galaxies. The example shown is NGC 1427A. (Credit: NASA, ESA, and the Hubble Heritage Team.) (d) Some galaxies are very bright, especially in the infrared, and are known as luminous infrared galaxies, or ultraluminous infrared galaxies (ULIRG). IRAS 1927–0406 shown here is an example of a ULIRG. (Credit: NASA).

that we can still observe (Figure 1.3(a)). A more evolved supernova remnant is shown in Figure 1.3(b). It is in the Large Magellanic Cloud, a neighbouring galaxy to the Milky Way. In 1987, another supernova occurred in the Large Magellanic Cloud. It (SN1987A) has become the best studied of all supernovae.

Supernova explosions eject material in large amounts, comparable to the mass of our Sun, from the interiors of stars into interstellar space. This ejected material is rich in the 'ashes' of the thermonuclear processes which power the stars, and these 'ashes' are the elements heavier than hydrogen. Less-massive stars also contribute to the enrichment of the interstellar medium with the 'ashes' of thermonuclear burning, albeit in a less dramatic way. The fact that we and our Earth are made predominantly from these elements, and that the Sun also contains them, indicates that the Solar System is made from 'recycled' material, that is, it was formed from interstellar gases containing the 'ashes' of a previous generation of stars. The picture that emerges from these general considerations is that as the galaxy evolves, stars are formed, and they 'age' and 'die', sometimes explosively. The ejected material enriches the interstellar medium with atoms of elements other than hydrogen, and the gases in interstellar space somehow condense to form a new generation of stars, and the cycle is repeated. In this scenario, we see that the interstellar medium plays a crucial role: it is the reservoir of mass for forming new stars and planets in any galaxy, even though it may at first seem a minor component of a galaxy, and it is continually enriched in the heavy elements that are the ashes of thermonuclear processes in stars.

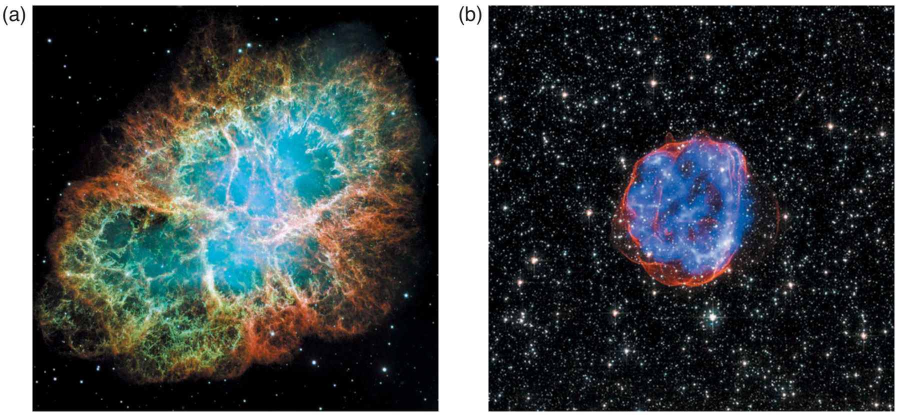

FIGURE 1.3 (a) The supernova remnant known as the Crab nebula. (Credit: NASA, ESA, J Hester, and A Loll (Arizona State University).) (b) An image of the supernova remnant SNR 0519690 which represents X-ray emission from very hot gas in the nebula as blue (Chandra Observatory) and optical emission in red (Hubble Space Telescope) from the outer boundaries of the nebula. (Credit: X-ray; NASA/CXC/Rutgers/J Hughes: Optical; NASA/STScI.)

1.2 EVIDENCE FOR MATTER BETWEEN THE STARS

Naked-eye observation of the Galaxy tells us nothing about interstellar space – except that it appears to be empty. However, this is easily seen to be an incorrect conclusion. Photographs from even low-powered telescopes provide the most striking and visually beautiful evidence of matter in interstellar space. Where interstellar gas is so near to a star that it is hot, it will radiate, and we can detect this radiation and identify it. We show later in this book images of some of these radiating regions.

The main evidence for the existence of interstellar matter rests, as we shall see in the succeeding chapters, on spectroscopy. The atoms, ions, and molecules in the interstellar gas may emit or absorb radiation corresponding to transitions between their various energy levels. A well-known transition is that of hydrogen atoms giving rise to the 21 cm radio line. Hydrogen atoms may also give rise to many other lines; the one giving the red colour prominent in many photographs of nebulae corresponds to the transition H(3p) → H(2s) at 656.3 nm. There are also other ways in which emission of radiation can occur, in particular over a continuum of wavelengths. All such radiation carries with it information concerning the interstellar medium, as we shall discuss in the following chapter.

Gravitational effects within the Galaxy also give indirect evidence for the existence of interstellar matter, and allow us to deduce an upper limit to the interstellar density. The argument goes as follows: a star situated at a distance z above or below the galactic plane experiences an acceleration, g_z, towards the plane due to the gravitational interaction of the star with all the mass in the Galaxy, stars plus gas. We cannot measure this acceleration for a single star. However, it can be deduced from the behaviour of a population of stars at various distances, z, from the plane, and so we may find g_z as a function of z. The total mass in the plane has a mean density, $\bar{\rho}$, which is related in a simple way to the rate of change of g_z with z, dg_z/dz, so $\bar{\rho}$ may be calculated. This mean density is found to be about 10^{-20} kg m^{-3} at the mid-plane. The known stars contribute to this mean density about 4×10^{-21} kg m^{-3}, so that the upper limit to the mass density of unobserved faint stars, other condensed objects, and the interstellar matter is 6×10^{-21} kg m^{-3}, or equivalent to about 2.7×10^{6} hydrogen atoms m^{-3}, allowing for 10% (by number) of the atoms being helium.

The centre of the Milky Way galaxy cannot be seen at optical wavelengths but is revealed at infrared wavelengths, see Figure 1.4.

1.3 PREVIEW

In this book, we are concerned with the physics of the interstellar medium in the Milky Way galaxy, but we shall particularly bear in mind the intimate relation between interstellar matter and galactic evolution through star and planet formation. The picture outlined in Section 1.1 – in which gas clouds collapse to form stars which themselves age and die, sometimes explosively – gives a direction to the chapters.

FIGURE 1.4 The centre of the Milky Way, about 8 kpc distant from the Sun, cannot be observed at optical wavelengths because of interstellar extinction along that path. This false-colour image in the infrared (data from NASA's Spitzer Space Telescope) gives a clear view of the centre, showing emission from warm dust (in red), the presence of enormous numbers of cool stars (in blue), and an intense radio source containing a supermassive black hole (in white). (Credit: NASA/JPL-Caltech/S Stolovy (Spitzer Science Center/Caltech).)

We begin by asking how astronomers obtain information about the interstellar medium (Chapter 2). What are the physical principles behind the formation of a spectral line? What other processes cause the emission and absorption of interstellar radiation? We end the chapter with a description of the broad types of interstellar regions that have been identified. Chapter 3 describes processes occurring between atoms, ions, and molecules and the effects these have on the interstellar gas. A rich chemistry arises from these gas phase processes, and the molecules formed provide probes of a wide variety of physical conditions. Chapter 4 is concerned with interstellar dust grains, and we shall discuss some of the interesting physics involved in describing these solid particles and the effects they have in the interstellar medium.

Chapter 5 gives special attention to those regions which are visually impressive in astronomical photographs, that is, those regions of space near hot stars where the gas is ionized and is emitting copious amounts of radiation. Chapter 6 gives an introduction to gas dynamics, which enables us in Chapter 7 to discuss some of the dramatic dynamical events occurring in interstellar space: for example, the expansion of ionized nebulae into cool gas, the effects of high-speed stellar winds on interstellar gas, and – most dramatically of all – supernova explosions. The final chapter looks at some of the physics that is fundamental to the problem of star formation. In this process, part of a gas cloud of density, say, 10^9 H_2 molecules m^{-3} must eventually become a star with a mean density of, say, 10^{30} H nuclei m^{-3}. This is an enormous transformation.

1.4 UNITS

Astronomy requires a large number of special units to describe in a convenient manner the quantities it measures or calculates. Thus, the solar mass, $M_\odot$, and solar luminosity, $L_\odot$, are convenient measures of the mass and luminosity of other stars, rather than the kilogram and candela, respectively. When measuring distance, it is more appropriate to use a unit such as a light year or a parsec. In general, however, the book is written in SI units, and any special units needed are defined in the tables on pp ix and x. An exception to standard SI usage is the adoption of the electron volt (eV) in describing energy levels within atoms and molecules, and multiples of eV (e.g. MeV) in describing the energies of cosmic rays. Temperature may conveniently be regarded as an energy measure. The table on p ix gives conversion factors for the energy units used here.

The SI units used here are for the convenience of physics undergraduates. If, as we hope, they refer to some of the astrophysical literature, they will find that an older and more traditional system is generally in use by astrophysicists. We sympathize with the more experienced readers, who will find familiar quantities appearing here with unfamiliar values.