PLASMAS

Julio J. Martinell, Rafael Navarro-Gonzalez, and Alejandro C. Raga
Plasma Physics Department, ICN, UNAM, México D. F., Mexico

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Contents

Summary

A general overview of physical phenomena that are due to the existence of plasmas is given. Some astrophysical processes that take place in the presence of the plasma in the medium are reviewed. Plasmas that appear briefly in the Earth's atmosphere are also described, such as lightning and auroras. A review is also made of plasmas produced by humans in the laboratory by different methods and for various purposes.

1. Introduction

The macroscopic world can intuitively be divided into solids and fluids. Of the fluids, we live immersed in air (a gas) and aquatic animals in water (a liquid). At temperatures of approximately ten thousand degrees Kelvin (or Centigrade, which is less by just 273 degrees from the Kelvin scale), the oxygen and nitrogen molecules (of which air is mainly composed) first dissociate into individual atoms, and then one (or more) electrons detach from the atoms. The gas is then composed of positively charged “ions” (mainly of nitrogen and oxygen) and negatively charged, free electrons. Such a gas, composed of positively and negatively charged particles, is called a plasma.

Plasmas share some properties with normal gases. For example, they can have motions (“flows”) which generate regions of high density (compressions) or low density (rarefactions), and they can vibrate at different frequencies (sound waves) or have strong perturbations (shock waves) moving at velocities higher than the sound speed.

The fact that the particles in a plasma are charged, however, allow a richness in behavior which is absent in neutral gases. In the presence of an electric and/or a magnetic field, the charged particles in a plasma interact with these fields, and the motion of the plasma can be strongly altered. Also, a localized motion of the plasma itself can generate electric and magnetic fields, influencing the motion of the plasma at the same or other locations. This feedback can produce “collective phenomena” in which an extended spatial region of a plasma can react to a localized perturbation. This kind of behavior is not present in an electrically neutral gas.

Many astrophysical and geophysical phenomena involve plasmas. Most astrophysical objects (for example, stars and nebulae) are made of gas which is at least partially ionized, so that it is strongly coupled to the local magnetic field. In particular, the highly ionized solar wind reaches the Earth, and it interacts with the Earth’s magnetic field (the Earth’s “magnetosphere”). Two important geophysical phenomena involving plasmas are aurorae and lightnings. There are also many laboratory experiments which involve plasmas. Some experiments are of particular relevance for studies of the possibility of generating energy through controlled nuclear fusion. Others are used for technological applications involving material processing.

This chapter discusses some of the research that has been done on astrophysical (Section 2), geophysical (Section 3) and on laboratory plasmas (Section 4).

2. Astrophysical Plasmas

2.1. Introduction

The most prominent astrophysical object is of course the Sun, and (not counting the moon and the other planets of our system) the much more faraway stars which we see at night. Stars have central temperatures exceeding ten million degrees (Kelvin or Centigrade), and surface temperatures ranging from a few thousand up to one hundred thousand degrees. Therefore, most of the volume of stars is composed of ionized plasmas.

Many of the more interesting plasma phenomena actually occur in the dilute gas which fills in the space in between the stars. These interstellar regions are occupied either by gas which was already present when the galaxies were formed, or by gas ejected by stars (in the form of winds or of supernova explosions). In the following three subsections, we discuss examples of interstellar plasmas.

2.2. Bright and Dark Clouds in the Interstellar Medium

The volume of space in between stars and galaxies is filled with a very tenuous gas (the "interstellar" or "intergalactic" medium). This all pervasive gas is concentrated in certain regions, and out of these denser regions of the interstellar medium new stars are formed. The radiation emitted by the recently formed stars then heats and ionizes the surrounding gas, forming the so-called "ionized nebulae". Figure 1 shows an image of the Great Nebula in Orion (which can just barely be seen with the naked eye) obtained with the Hubble Space Telescope (HST), which is an example of a nebula ionized by stars that have recently formed within it.

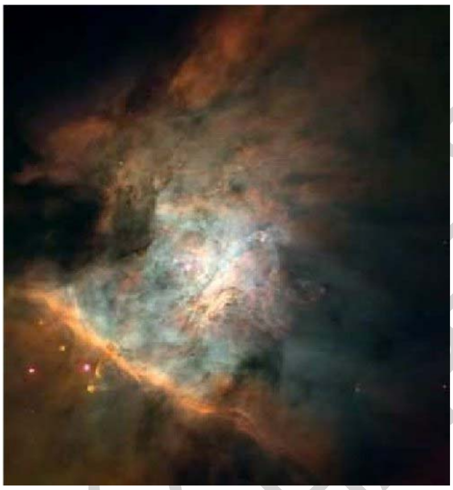

Figure 1: Mosaic of images obtained with the HST covering the Great Nebula in Orion (M 42). The different colors represent the emission in different emission lines.

The high density regions out of which stars are forming are initially cold (with typical temperatures of 10 degrees Kelvin) and are composed of gas in molecular form. Such clouds can be seen because they absorb the light emitted by background stars (the "coal sacks" superimposed on the southern Milky Way can be seen with the naked eye) and because they emit energy at the wavelengths of radio waves. Even though these clouds are dense and cold, high energy photons and particles emitted in other regions penetrate these clouds, producing a low fraction of ions and electrons (typically, about one in one hundred thousand of the molecules are ionized, producing free electrons). This rather low fraction of ions, however, produces a strong coupling with the local magnetic field, so that the gas in these cold regions still behaves like plasma.

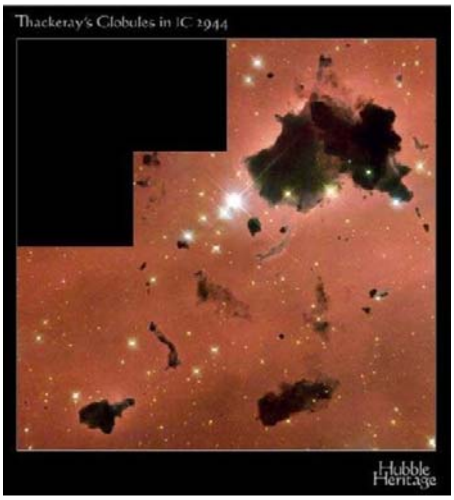

Figure 2: Thackeray’s globules are dense clouds of molecular gas which are in the foreground of the photoionized region IC 2944. The large globule in the top of the image actually covers the star (or stars) which are exciting the nebula. This is an image obtained with the HST in the light of the Hα line of hydrogen.

In some regions, the radiation from recently formed stars ionizes part of the surrounding interstellar medium, but it fails to ionize some of the denser regions. These still neutral regions can then be seen as dark clouds superimposed on the emission from the ionized gas. Figure 2 shows Thackeray’s Globules, which are a striking example of a group of dark clouds in front of an ionized nebula.

2.3. The Formation of Low Mass Stars and Planets

Large numbers of stars are presently forming in the denser regions of the interstellar medium of our galaxy. The more massive stars (with masses of 10 to 30 solar masses) emit a lot of radiation, which produces the ionized nebulae described in the previous section.

The newly formed, low mass stars (with masses comparable to the mass of our sun) do not produce enough radiation to ionize a substantial region of the surrounding interstellar medium. However, these stars eject strong “jets”, which travel away from the star at highly supersonic velocities. An example of such a jet is shown in Figure 3.

It is believed that these jets are a direct result of the process through which low mass stars are formed. In this process, the gas in a rotating cloud is first compressed by an external perturbation (which could result, for example, from a collision with another dense cloud), and then starts to collapse due to the increased gravitational force resulting from the compression. Because the cloud is rotating, only part of the gas can directly collapse onto the central, high density region (out of which a star will be formed), and the rest ends up being distributed in a flat, rotating structure. These flattened structures are called “circumstellar disks” or “protoplanetary disks”. The material in the disk spirals into the central star, and part of it eventually settles onto the star, while the rest gets ejected in the form of jets (see Figure 3). It is also believed that planetary systems are formed within these circumstellar disks.

Figure 3: HH 46/47 is a jet ejected by a young, low mass star (not visible optically) which is situated close to the left hand corner of the image. The jet is composed of material which travels outward from the star (towards the top, right hand corner of the image). The different colors represent the emission in different emission lines, as observed with the HST.

Until about twenty years ago, there were only indirect evidences for the existence of circumstellar disks. However, in the last two decades there have been many observations in which direct images of circumstellar disks have been obtained. For example, many circumstellar disks around young, low mass stars have been detected as shadows in front of ionized nebulae (see Figure 4). Several groups of scientists are now trying to obtain theoretical and observational connections between these disks and the planetary systems which have been discovered within the last decade around approximately 100 nearby stars.

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Biographical Sketches

Julio J. Martinell. Ph.D. in plasma physics in 1986, Massachusetts Institute of Technology (USA). Since 1986 Instituto de Ciencias Nucleares, UNAM (Mexico). Visiting scientist U. of Maryland (USA) in August 1996 - August 1997, and Politecnico di Torino (Italy) in August 2002 - August 2003. Sistema Nacional de Investigadores, level I since 1987. Areas of interest: Theoretical plasma physics, Thermonuclear fusion, Plasma astrophysics. Main contributions in: plasma transport in toroidal systems, plasma stability, magnetic reconnection in plasmas, relaxation phenomena.

Rafael Navarro-Gonzalez, Ph.D. in chemistry in 1989, University of Maryland-College Park (USA). Postdoc at the Univ. of Maryland (1991-1992). Research professor at the Instituto de Ciencias Nucleares since 1989. Visiting Professor of the University of Maryland, Massachusetts Institute of Technology, University Denis-Diderot (Paris 7), UniversitÃ© Val de Marne Paris 12) and Directeur de Recherche Associate au Centre National de la Recherche Scientifique (France). Prize of the Universidad Nacional Autónoma de México as outstanding young scientist in natural sciences (1998); first recipient of the Molina fellowship on environmental sciences (1997). Areas of interest: Lightning chemistry, Planetary and Atmospheric sciences and Astrobiology. Main contributions in: role of lightning in the evolution of life, discovery of Mars-like soils on Earth

Alejandro C. Raga, Ph.D. in astronomy in 1985, University of Washington (USA). Postdoc at the Univ. of Washington (USA), at the Canadian Institute for Theoretical Astrophysics, and at the University of Leeds (UK). Faculty member at UMIST (Manchester, UK), and research scientist at the Instituto de Astronomía (1995-2001) and the Instituto de Ciencias Nucleares (since 2001). Prize of the Academia Mexicana de Ciencias (área de Ciencias Exactas, 1998), Fellow of the John Simon Guggenheim Memorial Foundation (2000/2001). Areas of interest: Dynamics of the interstellar medium, Gasdynamics Main contributions in: jets from young stars, photoionized regions