ASTROPHYSICS

Ionizing the Galaxy

Ronald J. Reynolds

Ionized hydrogen is found throughout interstellar space. This has been known for almost 30 years, since the discovery of pulsars and the dispersion of their radio pulses by the free electrons that have been stripped from the atomic hydrogen along the line of sight (*1*). The source of this ionization still remains a mystery, however, challenging conventional wisdom about the interstellar medium and the principal mechanisms of ionization and heating within the disk and halo of our galaxy. More recently, extensive ionization similar to that in the Milky Way has been found in other galaxies (*2–4*). Speculation about the source of this ionization has been wide ranging, including such traditionally accepted sources as hot stars (*5, 6*) as well as more exotic possibilities like galactic magnetic flares (*7*), intense cosmic-ray electrons (*8*), and the decay of dark-matter particles (*9*).

Progress toward understanding this diffuse ionized gas (sometimes called DIG for short) should soon come from new observational techniques that are incorporating narrow-band optical filters with sensitive charge-coupled device (CCD) cameras to detect very faint optical emission lines from the gas (*10–12*). This emission, composed primarily of hydrogen recombination radiation and transitions from metastable states in such trace ions as singly ionized nitrogen and sulfur, covers the sky with a faint red glow and contains a wealth of information about the distribution and motions of the ionized gas as well as its temperature and ionization state. However, because the emission is so faint, comprehensive investigations have had to await the development of sufficiently sensitive detection techniques, particularly the modern CCD imaging detector.

One of the most sensitive of the new instruments (*12, 13*) began operating at the Kitt Peak National Observatory near Tucson, Arizona, earlier this year. WHAM (Wisconsin H-Alpha Mapper) will be providing astronomers with their first detailed look at the actual distribution and kinematics of the DIG across the sky (see Fig. 1). This new picture of our galaxy is being synthesized from thousands of spectra collected every clear moonless night over an 18-month period that began in January. Each spectrum samples a 1° patch on the sky and measures the intensity and Doppler shift of the very faint hydrogen Balmer–alpha (H-alpha) line emitted by the DIG in that direction (*14*).

The ultimate goal is to understand the nature of interstellar matter and its role in star formation and the evolution of the galaxy. The interstellar medium is composed primarily of neutral atomic and molecular hydrogen, which is spread throughout the galactic disk with an average density of about one atom per cubic centimeter. It is the material out of which new stars are created, and it is the material into which old stars deposit their remains as the galaxy evolves, slowly turning the interstellar matter into ever more stars and planets. In a complex feedback loop that is not understood, the conditions in the interstellar medium that give rise to the next generation of stars are determined by the medium's interactions with the previous generations of stars.

One of these interactions is the ionization of hydrogen by ultraviolet radiation from recently formed, massive stars called O stars. The O stars, with effective surface temperatures near 40,000 K, emit much of their light in photons having energies greater than 13.6 eV, the ionization potential of atomic hydrogen. The radiation ionizes and heats the surrounding interstellar gas, dramatically increasing its pressure and disrupting the dense cloud from which the star was born. The result can be seen in deep sky photographs as beautiful emission nebulae, such as the famous Rosette Nebula (see Fig. 2) glowing in the red H-alpha line of the recombining ionized hydrogen (see Fig. 2).

The formation of this glowing zone of ionized hydrogen around an O star was first described by the astronomer Bengt Strömgren in a classic 1939 paper (*15*). A principal conclusion of Strömgren's paper was that ionized interstellar hydrogen "should be limited to certain rather sharply bounded regions in space surrounding O-type stars or clusters of O-type stars" (p. 526). This is because the mean free path length of a hydrogen-ionizing photon in the neutral atomic regions of the interstellar medium is very short, much less than the typical 100–light year radius of one of these ionized regions, or "Strömgren Spheres," as they are commonly called. Therefore, any ionizing photon that finds itself beyond the Strömgren Sphere's outer boundary is absorbed almost immediately within the neutral gas. The many photographs of emission nebulae around O stars appear to provide observational evidence for Strömgren Spheres, and because O stars and clusters of O stars are very few and far between in the galaxy, the conclusion that ionized hy-

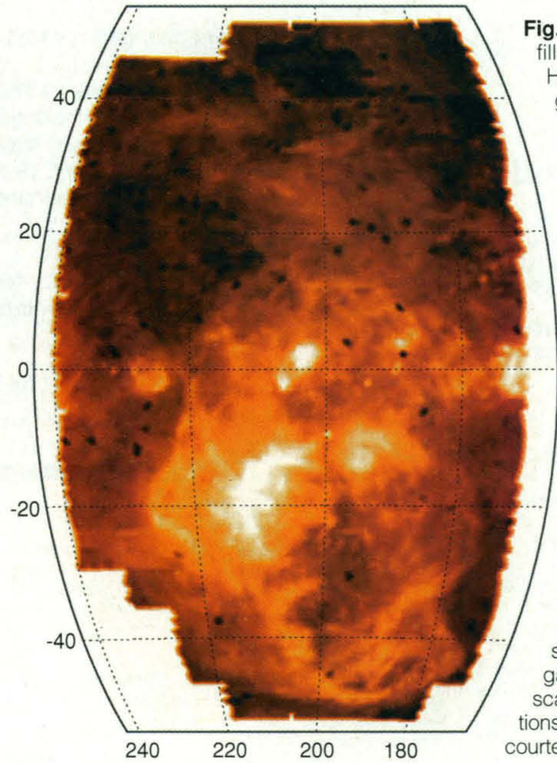

Fig. 1. A wide-angle view of the sky filled with faint filamentary and diffuse H-alpha emission from ionized hydrogen in the interstellar medium. This picture, covering almost two steradians of the winter sky as seen from Kitt Peak, Arizona, was made from ~7000 WHAM spectra containing information about the velocity of the emitting gas along the line of sight in addition to its distribution across the sky. The image shows those portions of the interstellar medium that are moving toward Earth with a velocity between –18 and –30 km s^{-1} with respect to the local galactic rest frame. The midplane of the Milky Way runs horizontally through the center; coordinates are in degrees of galactic longitude (abscissa) and latitude (ordinate). The areas of brightest emission are white and are generally associated with emission nebulae (Strömgren Spheres) around O stars near the galactic midplane. The Rosette Nebula is the small white spot at galactic coordinates 206, –2. Black dots scattered throughout the image are directions contaminated by starlight. [Figure: courtesy of L. M. Haffner]

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Fig. 2. The Rosette Nebula. A 1° diameter Strömgren Sphere. [Courtesy of Anglo-Australian Observatory]

PHOTO: DAVID MALIN

drogen can exist only in very limited regions of the interstellar medium is quite compelling.

The presence of wide spread ionization (the DIG) in our galaxy and others therefore implies that something is seriously wrong, or at least very incomplete, with this picture. Both pulsar dispersion measurements (*16*) and the subsequent detections of very weak, diffuse H-alpha from the interstellar medium (see Fig. 1) have provided convincing evidence that ionized hydrogen is spread throughout vast regions of the galaxy where the hydrogen was supposed to be completely neutral, regions that are far from O stars and well outside the classical Strömgren Spheres.

So what is going on? The only known source of ionization with sufficient power to produce the DIG is the galactic population of O stars, but their ionizing radiation does not appear capable of permeating the galaxy. Perhaps the Strömgren Sphere argument can somehow be circumvented. For example, it has been shown that certain fractal (*17*) or other distributions (*5*, *6*) of the neutral hydrogen can make the interstellar medium more transparent to an O star's ionizing photons. The alternative—that there is another significant source of ionization in the galaxy that has not yet been identified—is also possible. This source would have to be almost as powerful as the O stars but much more diffusely distributed throughout interstellar space. Although a number of such sources have been proposed (*7–9*), none has yet been confirmed. New clues uncovered by the optical emission line studies should soon begin to resolve this long-standing mystery.

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SURFACE PHYSICS

More Than Skin Deep

Ward Plummer

Electrons are normally not supposed to wander very far from metal surfaces. Yet on page 1480 of this issue, Höfer *et al.* (*1*) report an interdisciplinary investigation that catches surface electrons at their most adventurous. By combining laser techniques used so successfully in atomic, molecular, and semiconductor physics (*2–4*) with angle-resolved photoelectron spectroscopy, the workhorse of surface science (*5*), Höfer *et al.* give us a glimpse of the time evolution of electronic states at a metal surface. For the first time, quantum beats between coherently excited states at a clean metal surface have been observed, allowing the authors to resolve high-order states, inaccessible with standard photoelectron spectroscopy. Coherent excitation of higher order Rydberg-like states, selected by the energy in the photoelectron spectrometer, display dramatic time evolution as a consequence of the motion of the wave packet, which travels about 200 Å away from the surface into the vacuum and then returns with a period of 800 fs.

The highly excited states in an atom or molecule are referred to as Rydberg states because their energy separation resembles that predicted by Rydberg for the hydrogen atom. A similar series of excited states exists on many metal surfaces called image potential states (*6*). They are quantum states trapped in the image potential well, where the classical image potential is $V(z) = -e^2/4z$ (z being the perpendicular distance above the surface). In most metals there is no barrier for an electron to return to the metal, but in a few metals there is a band gap near the vacuum level, and an excited electron is trapped in the quantum states of the image potential. The resulting quantized electronic states form a Rydberg-like series with an energy level scheme given by

$$E_n = -0.85\ \text{eV}/(n + a)^2 \qquad (1)$$

where n is a positive integer and a is a "quantum defect" to account for the nature of the penetration of the electron wave function into the solid, within the band gap.

The figure shows a semiclassical picture of the motion of an electron in an image potential state (filled circles), accompanied by its image charge (open circle) inside of the metal. Image potential states have been studied for years with laser-based two-photon photoemission (2PPE). The first laser pulse (green pump laser in the figure) excites an electron from below the Fermi energy (occupied states) in the metal into an image potential state. The second laser pulse (probe laser) excites the electron in the image state into the continuum above the vacuum level. The photoelectron spectrometer is used to determine the energy of the emitted electron and consequently the energy of the image state.

Undoubtedly, the most interesting image states are the high n states, which extend far into the vacuum (200 Å for $n = 7$), but these states are not easily accessible to conventional 2PPE spectroscopy. There are two limitations: (i) the spacing of the energy levels soon becomes smaller than the resolution of the best analyzer, and (ii) the photoionization cross section dies off rapidly with increasing n. The decrease in cross section is simply a consequence of the fact that electrons in free space cannot absorb a photon and conserve both energy and momentum. Photoexcitation occurs near the surface where the rapid gradient in potential serves as a source of momentum (*7*). The highest resolution at present is 15 meV in measurements by Padowitz *et al.*, where the first four image states were observed (*8*). Höfer *et al.* were able to determine the energy of the fourth, fifth, and sixth image potential state

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