# 28

PRISCILLA C. FRISCH*

# The interstellar medium of our Galaxy

Over the past century our picture of diffuse material in space has grown from a simple model of isolated clouds in thermal equilibrium with stellar radiation fields to one of a richly varied composite of materials with a wide range of physical properties and morphologies. The Solar System interacts with a dynamical interstellar medium. Optical, radio, and UV astronomy allow us to study the clouds which form the galactic environment of the Sun. The composition and distribution of interstellar clouds in the disk and halo tell us about the history of elemental formation in our galaxy, and the past and future environment of the Solar System.

Dark lanes of dusty clouds obscuring portions of the Milky Way are celestial landmarks, but the realization that interstellar gas pervades space is quite recent. The twentieth century opened with the discovery of a "nebulous mass" of interstellar gas in the sightline towards the binary star $\delta$ Orionis (Hartmann 1904). A series of over 40 spectra showed that the Ca II K line (3933 Å) absorption was nearly stationary in wavelength, "extraordinarily weak," and "almost perfectly sharp," in contrast to broader variable stellar absorption features. Sharp stationary Na I D1 and D2 lines (5890, 5896 Å) were discovered in $\delta$ Ori and $\beta$ Sco by Mary Lea Heger. An explanation offered was that a stationary absorbing cloud of vapor was present in space between these binary systems and the observer. The Ca II and Na I lines constituted the primary tracer for interstellar gas during the first half of the century.

Interstellar matter (excluding dark matter) provides about 30–40% of the galactic mass density in the solar neighborhood. Trace elements heavier than He, which form the planets, record the chemical evolution of matter in our Galaxy, and provide detailed information on physical conditions in interstellar clouds, represent a small proportion of the interstellar atoms (~0.15%). These same elements trace the metallicity of interstellar gas, and by inference the mineralogy of interstellar grains. A primary goal of interstellar medium studies has been to determine the chemical composition of interstellar clouds compared to, for instance, normal Population I stars such as the Sun. Space observations are required to observe most astronomically interesting elements such as C, N, O, Fe, Mg, and Si, since the resonant ground state transitions of these atoms fall in the ultraviolet (UV, 912–3000 Å).

Gene Parker once asked me "What is an interstellar cloud?" The Rashomon-like answer depends on the context. Early optical data showing velocity components in interstellar absorption lines led to a definition of "clouds" as discrete kinematical units. Alternative descriptions were based on the physical properties of the clouds, for example warm diffuse intercloud material in equilibrium (Stromgren 1948, Field *et al*. 1969), or hot tenuous coronal gas (Spitzer 1956) to confine the clouds. Ground and space data now show interstellar material (ISM) with densities in the range $10^{-4}$ atoms cm$^{-3}$ to over $10^3$ atoms cm$^{-3}$, kinetic temperatures $20\,K < T_k < 10^6\,K$, and many levels of ionization. Within 10 pc of the Sun, we see density contrasts of over 400 and temperature contrasts over 100. The distinction between turbulence and "clouds" has been blurred by recent high-spectral resolution data showing that low-resolution spectral data may miss over half of the velocity components in a sightline (Section 3.2), and that ~15% of the mass of cold clouds is contained in tiny (AU-sized) structures (Section 3.1). Are these features "clouds" or manifestations of a turbulent ISM? The discovery of interstellar clouds in the galactic halo (Münch 1957) added new questions about the stratification of ISM in the gravitational potential of the Milky Way Galaxy, and the origin of halo gas.

Surprisingly, interstellar gas constitutes about 98% of the diffuse material inside of the heliosphere, and subparsec spatial variations in interstellar cloud properties near the

* University of Chicago, IL, USA

*Priscilla C. Frisch, The Century of Space Science, 647–675*

Sun indicate the solar environment could change on time scales $\approx 10^4$ years. Shapley's conjecture in 1921 that interstellar clouds affect planetary climates no longer seems outlandish.

Symbols used here are $N$ (column densities, $cm^{-2}$), and $n_H$ (total volume density for all forms of H, $cm^{-3}$). Early optical and 21 cm radio data were insensitive to clouds with column densities $N(H) < 10^{19}\,cm^{-2}$. UV observations of trace elements can detect kinematical objects with $N(H) \gtrsim 10^{16}\,cm^{-2}$. Galactic longitudes and latitudes are quoted in System II. (System II was adopted by the International Astronomical Union in 1958 in order to correct earlier errors in the location of the galactic center. Galactic coordinates published before 1958 are incorrect.) The local standard of rest (LSR) velocity frame represents heliocentric velocities transformed to the rest frame corresponding to the mean motion of comparison stars near the Sun, where the comparison set is selected according to some criterion. (Most LSR interstellar velocities presented in the twentieth century assumed, frequently without explanation, a "standard" solar motion corresponding to a velocity of $19.7\,km\,s^{-1}$ towards the apex position $l^{II} = 57°$, $b^{II} = +22°$. Recent Hipparcos results give a solar motion of $13.4\,km\,s^{-1}$ towards the apex direction $l^{II} = 28°$, $b^{II} = +32°$.) Radio data are usually presented in the LSR velocity frame, where this issue is particularly troublesome.

This chapter focuses on the diffuse gas in the space between the stars of our Galaxy. For an eloquent summary of the physical properties of the ISM and data up to the mid-1970s, see Spitzer (1978).

## 1 DISCOVERING INTERSTELLAR GAS

The observational and theoretical foundations of ISM space studies were formed in the first half of the twentieth century. In 1926 Sir Arthur Stanley Eddington laid out the principles of the ionization equilibrium of atoms in space under the influence of dilute stellar radiation fields (the Bakerian Lecture, Eddington 1926). He evaluated the importance of the short wavelength stellar radiation field ($\lambda < 800$ Å) for cloud heating (although extreme ultraviolet radiation from space was not observable in 1926), and concluded that diffuse clouds are illuminated by a radiation field at a Planck temperature of 10,000 K and have kinetic temperatures $T_k \sim 10{,}000$ K. He found frequent collisions would establish Maxwellian velocity distributions for electrons and ions in space. Eddington concluded that the material creating the stationary Ca II and Na I absorption lines is uniformly distributed, and argued that stellar dynamics implied $n_H \leq 10\,cm^{-3}$ for diffuse material. He determined that in space most interstellar Ca is Ca III and most Na is Na II He "reluctantly" concluded that dark nebulae derive their obscuration from "fine solid grains." Eddington noted that radiation with energies greater than ~13.6 eV (the ionization potential of hydrogen) would be prevented from entering clouds by abundant hydrogen, and concluded interstellar $H_2$ would be abundant.

In the early part of the century, Harlow Shapley advanced the idea that interstellar clouds were linked to terrestrial climate shifts. He noted that the diffuse luminous and dark nebulae are found throughout space, and that the Sun was receding from the Orion region where dark nebulae are prominent (Shapley 1921). Shapley suggested that a past climate-altering encounter between the Orion molecular clouds and the Solar System, would yield a 20% variation in solar radiation, which if sustained for a period of time would alter Earth's climate. While encounters with dense clouds as envisioned by Shapley are statistically improbable, encounters with clouds of modest density ($\sim 10\,cm^{-3}$) are much more likely and would destabilize the heliosphere and modify the interplanetary environment (Zank and Frisch 1999).

### 1.1 Optical absorption lines

The interstellar nature of the sharp stationary absorption features seen in binary systems was quickly established. Plaskett and Pearce (1930) provided a convincing discussion that the sharp Ca II and Na lines are formed in diffuse space, and labeled these features "interstellar." Observations of 1700 stars with $V < 10.5$ mag by Otto Struve had shown that K line strengths in general increase with increasing magnitude (and thus distance), suggesting an interstellar origin. Plaskett and Pearce measured Ca II K line velocities for ~250 OB stars (to within $\pm 1.8\,km\,s^{-1}$), and found they are "almost exactly twice" interstellar Ca II motions expected for the galactic rotation of interstellar clouds located at half the distance to the background star. Peculiar motions within the clouds were found to be equally important for line broadening.

During the late 1930s, Merrill and collaborators surveyed the yellow Na I D1, D2 and blue Ca II H, K lines in over 400 hot, bright stars. The D2/D1 line ratios were seen to increase as total line intensity decreased, providing an early indication of line saturation. The formula relating absorption line equivalent width ($W$) and column density ($N$) was found to be faulty for "deep" lines, leading to the development of an empirical "curve of growth" (COG) using the doublet ratio (Ca II H/K, Na I D1/D2) to constrain the functional dependence of $W$. The COG, formalized later by Stromgren (Section 1.3), has been used to derive column densities from the equivalent widths of interstellar absorption lines for 70 years. Cloud motions were shown to depend on star distance, with velocity–longitude plots showing a double sine pattern with an amplitude at half the expected galactic rotation value (e.g., see review of

Münch 1968). The bulk motions implied by line velocities showed a chaotic or turbulent component, with dispersion $v_{radial} = 5$–$10\,km\,s^{-1}$, which was interpreted as moving "clouds" or "currents." The Na I line strengths increased with both distance and the amount of interstellar "smoke" (now known as dust) in the sightline (where the dust was determined by the reddening of starlight).

The chemical composition of interstellar clouds was explored by a series of observations at Mt. Wilson, Lick, and the Dominion Astrophysical Observatories. Sharp interstellar absorption lines from Na I ($\lambda\lambda$3302.4, 3303.0, 5895.9, 5890.0), Ca I ($\lambda$4226.7), Fe I ($\lambda\lambda$3719.9, 3859.9), Ti II ($\lambda\lambda$3383.8, 3242.0, 3229.2, 3073.0), K I ($\lambda\lambda$7664.9, 7699.0), CH II ($\lambda\lambda$3957.7, 4232.5), CH I ($\lambda\lambda$4300.3, 3890.2), and CN I ($\lambda\lambda$3875.8, 3874.0) were discovered, and upper limits were placed on Al I ($\lambda$3944.0), Sr II ($\lambda\lambda$4077.7, 4215.5), and Ba II ($\lambda\lambda$4554.0, 4934.1) lines (e.g., see review of Münch 1968). The sightlines towards $\chi^2$ Ori and 55 Cyg were shown to be excellent for identifying new interstellar lines (Dunham 1939). Dunham used the weak 3302 Å and strong D1, D2 Na I doublets to construct an empirical COG for the ISM towards $\chi$2 Ori, avoiding saturation problems with the D lines. Ionization equilibrium calculated for $N$(Ca I)/$N$(Ca II) provided the interstellar electron density, $n_e \sim 0.7$–$1.4\,cm^{-3}$. The anomalous properties of interstellar Ca II lines were apparent in early data. These observations yielded $N$(Ca II)/$N$(Na I) $\ll 1.5$, which was the value expected from stellar atmosphere data at that time.

The peculiar behavior of interstellar Ca seen in these early data was a harbinger of the fundamentally different properties of volatiles and refractory elements in the ISM; however, an incomplete understanding of cloud ionization prevented this recognition. When Olin Wilson showed convincingly that Ca II has a velocity distribution which is peculiar in comparison to Na I, he described the results as "unexpected … and disappointing." The average internal velocity distribution for Ca II was about three times larger than for Na I ($22\,km\,s^{-1}$ *v.* $7.5\,km\,s^{-1}$; Wilson 1939). Although later high-resolution spectroscopy showed that the "lines" observed by Wilson were blends of several components (Section 3.2), the velocity distribution of Ca II was still peculiar. Merrill and Wilson showed that the ratio $N$(Na I)/$N$(Ca II) varied strongly from one cloud to another, with values <0.3–10 (e.g., see review of Münch 1968).

Walter S. Adams published an influential survey of the strengths and velocities of Ca II H, K, lines and weak features from CN I, CH I, CH II, Fe I, and Ca I in ~300 disk ($|z| < 500\,pc$) OB stars visible from the northern hemisphere (Adams 1949). The higher resolution of these data ($\sim 6\,km\,s^{-1}$), compared to earlier photographic data, demonstrated that interstellar gas is concentrated in clouds with velocity separations larger than the atomic velocity dispersion within individual clouds. The velocities in this survey provided a consistent survey of cloud kinematics. Adams estimated the relative strengths of the Ca II lines by visually estimating line strengths, which was a common practice then; the weakest features he detected correspond to equivalent widths of ~3 mÅ. Half of the stars in the sample were found to have complex H or K lines, while about six stars showed weak Ca II absorption at 4226 Å. About 25% of the stars had weak blue/near-UV features from CN I, CH I, CH II, Ca I, or Fe I. Adams found 21 Ca II line components with $v_{lsr} > 30\,km\,s^{-1}$ (the velocities quoted in Adams (1949) should be updated with modern wavelengths), and concluded the velocities represented peculiar cloud motions through the LSR.

Blaauw used Adams' data to determine the form of the velocity distribution of the chaotic component of interstellar cloud velocities (e.g., see review by Spitzer 1968). He compared Ca II component velocities with two possible distributions – a Gaussian and an exponential distribution of component velocities. Blaauw concluded that an exponential form fitted the observed velocity distributions better than a Gaussian form. Munch extended this analysis to halo stars, with observations of Ca II and/or Na I towards 112 stars in the northern hemisphere sky ($l = 50°$–$160°$, $|z| = 1$–$2\,kpc$; Münch 1957). He confirmed earlier studies showing that bulk cloud motions indicate clouds are aligned with the Orion and Perseus spiral arms, and found blue-shifted absorption components from expanding interstellar gas around O-star associations. Based on the Blaauw results, and reasoning that turbulence is not Gaussian so that the increased energy dissipation by supersonic turbulence would flatten a cloud velocity distribution in comparison to a Gaussian, Münch fitted the observed disk and halo cloud velocities with the form:

$$\Psi(V) = \frac{1}{2\eta}\exp(-|V - V_o|/\eta)$$

where $\eta$ is the mean radial velocity, found to be $\sim 5 \pm 1\,km\,s^{-1}$ by Blaauw. With the exponential distribution, a constant value for the velocity dispersion for all Na I D2 line strengths is obtained ($\eta\sqrt{2} \sim 4.6\,km\,s^{-1}$), providing a better fit to velocity distributions than a Gaussian form. This has created what I view as a conundrum, since the internal velocity distributions of clouds are found to be Gaussian in cold clouds, while the bulk cloud velocities measured at higher resolution show an exponential distribution.

A study of the abundance variations between individual clouds was presented in a classic paper by Routly and Spitzer, in 1952, which confirmed earlier indications that the distribution of Ca II cloud velocities is intrinsically larger than the distribution of Na I velocities. They found both that $b$(Ca II) > 1.5 $b$(Na I) and that Ca II component velocities are larger than for Na I. The systematic decrease of $N$(Na I)/$N$(Ca II) with increasing cloud velocity is known as the "Routly–Spitzer (RS) effect", manifested as $N$(Na I)/$N$(Ca II) $\lesssim 1$. RS proposed that the process accelerating Ca II also decreased $N$(Na I)/$N$(Ca II), either through collisional ionization of Na I during acceleration, or from relative differences between Ca and Na depletions onto dust grains in low- $v$. high-velocity clouds. The first discovery of ISM within 20 pc of the Sun was possible because of the RS effect. Ca II was detected towards $\alpha$ Oph (14 pc), but not Na I (Munch and Unsold 1962). Recent data give $N$(Na I)/$N$(Ca II) $\sim 0.1$ in the $V_{lsr} \sim -8$ km s$^{-1}$ cloud towards $\alpha$ Oph (Welty *et al*. 1996). Small-scale ($\sim 1°$) variations in Ca II line strengths suggested the presence of small clouds (<1 pc). These data provided the first evidence of small-scale structure and shocked ISM close to the Sun.

As frequently happens, new techniques proven in first-generation instruments provide limited data, but change the course of science. The first high-spectral-resolution ($R >$ 200,000) observations of optical absorption lines did not achieve the initial goal of observing the Na I D line hyperfine components (separated by $\sim 1.0$ km s$^{-1}$), but instead demonstrated cloud velocity structure that is unresolved in photographic plates. High-spectral-resolution ($R = 3$–$5 \times 10^5$) spectrometers were developed to observe the hyperfine Na I lines towards $\alpha$ Cyg using the long-focal-length McNath solar telescope (Livingston and Lynds 1964), and using a Pepsios spectrometer at Lick Observatory (Hobbs 1965). Much later, after the launch of the Copernicus satellite and after high-resolution optical data were routinely acquired by Hobbs and others (Section 3.2), the Na I D-line hyperfine splitting was discovered towards $\alpha$ Cygnus, using a Michelson interferometer (effective resolution $R \sim$ 500,000; Wayte *et al*. 1978). Turbulence in cold interstellar clouds was found to be subsonic. The +1 km s$^{-1}$ cloud has $b_{Dop} = 0.38$ km s$^{-1}$ and a likely temperature of 70–124 K, indicating turbulent velocities $v_t = 0.26$–$0.3$ km s$^{-1}$ in comparison to the isothermal sound speed of $\sim 0.8$ km s$^{-1}$.

A thorough and now classic study of the ISM in front of $\zeta$ Oph (HD 149757) was performed by George Herbig, using the Lick Observatory 120-inch (3 m) Coudé feed spectra with photographic plates (Herbig 1968). The star $\zeta$ Oph has a relatively featureless bright continuum (O9.5 Vn, $V =$ 2.6 mag, 140 pc, $vsini = 380$ km s$^{-1}$), and a rich interstellar spectrum ($E(B - V) \sim 0.32$ mag) lending itself to searches for new interstellar species. It is a runaway star from the Scorpius–Centaurus association moving supersonically through the ISM (space velocity $\sim 40$ km s$^{-1}$), and with a circumstellar H II region (5° radius). $\zeta$ Oph also has a ram-pressure confined stellar wind observed around the star through 60 μm radiation from heated, swept-up interstellar grains. Herbig measured absorption lines from Na I, Ca II, K I, Ti II, Fe I, CH I, CH II, and CN I, and set limits on some 25 additional species at the $W = 1$–$2$ mÅ level. The ISM is contained in two dominant clouds at $-15$ km s$^{-1}$ and $-29$ km s$^{-1}$ (heliocentric velocities). An empirical curve of growth for the main component (heliocentric velocity, $v_{hc} = -15$ km s$^{-1}$) gives $b_{Dop} = 2.4$ km s$^{-1}$ and the column densities for these elements. The photoionization equilibrium of Na I, which equilibrates photoionization with the temperature-dependent recombination rate of Na$^+$ and an electron ($N$(Na II)/$N$(Na I) $\sim n$(Na II)/$n$(Na I); Section 1.3) gives $n_e = 0.36$–$0.54$ cm$^{-3}$ if the $-15$ km s$^{-1}$ cloud is $\sim 50$ pc from $\zeta$ Oph. If photoionization of heavy elements (e.g., C) supplies electrons, densities $n_H =$ 500–900 cm$^{-3}$ are found, indicating the cloud is a thin sheet of thickness $\sim 0.15$ pc. Later studies show Na is depleted by factors of 4–5, raising densities and reducing cloud thickness by the same factors. Enhanced abundances of Ca II and Ti II in the $-29$ km s$^{-1}$ cloud identify this material as "intercloud," which Herbig suggested is local (since it is seen in front of many Scorpius stars).

Lewis Hobbs initiated the high-resolution era of optical spectroscopy with a survey of the Na I D lines at resolution $\sim 1$ km s$^{-1}$ using a Pepsios interferometer at Lick Observatory (Hobbs 1969). Turbulence was found to dominate observed line widths, since cloud temperatures of 100 K yielded $b_{Dop} \sim 0.3$ km s$^{-1}$, $v$. observed Doppler widths of $b_{Dop} \sim 1.5$ km s$^{-1}$. The photoionization balance of Na applied to $N$(Na I)/$N$(H I) yielded typical electron densities $n_e \sim 0.008$ cm$^{-3}$ for solar abundances, or $n_H \sim 20$ cm$^{-3}$ if electrons are supplied by the photoionization of metals. High-resolution optical data acquired by Hobbs, his students, and others proved to be a crucial supplement to UV data (Section 3.2).

## 1.2 Radio astronomy – the first multispectral data

Radio waves provided the first multispectral window on the ISM. Radio emission from the Galaxy was discovered by Karl Jansky in 1932 during an investigation of radio static in a Bell Labs shortwave ($\sim 15$ m) radio antenna. Jansky recognized the interstellar origin of the hiss. Jansky's papers inspired Grote Reber, who, working with a private radio telescope located in his backyard in Wheaton, Illinois, in 1938, detected cosmic static at 2 m and confirmed Jansky's discovery. Over the next several years, Reber used his backyard telescope to map the northern hemisphere radio sky at 160 MHz and 480 MHz. The advent of World War II moved radio astronomy to the forefront of technical interest, both in the USA and Europe, and during the following decade technical advances from the wartime use of radar supported the development of the new radio sciences. Shklovsky (1960) reviews the scientific basis for the developing field of radio astronomy.

The spectral index of the cosmic "radio static" was measured and found to increase towards lower energies, in contrast to the expected increase towards higher energies predicted for a blackbody (or "thermal") source. This puzzle was explained when V.L. Ginzburg calculated the

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