DISTRIBUTION AND COMPOSITION OF INTERSTELLAR MATTER

E. E. Salpeter
Astronomy and Physics Department
Cornell University

1. INTRODUCTION

I am somewhat embarrassed to discuss ST observations of the interstellar medium (ISM) of our own Galaxy for two reasons. First of all it seems, at least at the moment, a less exciting subject for the ST than some others. Secondly, I sadly found, while reading the literature in preparation for this discussion, that I am not sufficiently familiar with optical astronomy to be able to guess where the real advances will come. As a consequence I shall merely summarize (a selection of) observations that have already been proposed, including some for the ISM in external galaxies. Unless otherwise stated, all observations for the high resolution spectograph (HRS) and the faint object spectograph (FOS) are described in more detail by Brandt et al (1977) and by Harms et al (1977), respectively. Observations for the wide field camera (WFC) and faint object camera (FOC), on the other hand, were already discussed at length at the ESA/ESO Workshop on "Astronomical Uses of the Space Telescope" and I shall refer to review papers in the workshop proceedings.

In Sect. 2 I mention some of the current problems about the ISM that interest me personally the most. The remaining sections summarize proposed observations of matter distribution (hopefully, abundances will be discussed by Jura and others). The reader will note a strong emphasis on the HRS over other instruments. This stems in part from the fact that we have learned so much from observations with the Copernicus satellite (Spitzer and Jenkins 1975) and the HRS is "bigger and better" by simultaneously providing better sensitivity and spectral resolution. I cannot guess whether the history of the ST regarding the ISM will indeed stress "bigger and better Copernicus observations" or whether (as often) quite unexpected discoveries will dominate.

2. SOME CURRENT PROBLEMS

My personal views on the various components of (and energy balance in) the interstellar medium (ISM) I stated just a year ago (Salpeter

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

1979), so I will list only some current problems. Many of these problems were already described in books and reviews (Dalgarno and McCray 1972, Aannestad and Purcell 1973, Osterbrock 1974, Spitzer and Jenkins 1975, Audouze and Tinsley 1976, Chevalier 1977, Salpeter 1977, Spitzer 1978, McCray and Snow 1979).

For the components of the ISM which contain predominantly neutral, atomic hydrogen one usually talks of "clouds" (or "diffuse clouds") on the one hand and the intercloud medium on the other. It is not clear to what extent the "clouds" are really isolated entities (Heiles 1976) and to what extent the intercloud medium is all-pervasive. More data on correlation between spatial, temperature and velocity structure would be useful. The dense, "molecular clouds" make up an appreciable fraction of the mass of the ISM and are presumably the site of star formation, but quantitatively there is a puzzle: These clouds ought to be in free-fall, free-fall times should be short and the clouds should "turn over" much faster than they seem to. It would be nice to know if something is keeping these clouds in a delicate balance against gravitational collapse (Solomon et al 1979).

The overall fluxing of mass, bulk kinetic energy, thermal energy and ionization through the ISM is understood in broad outline, but questions remain on quantitative details: Is most of the massloss from stars accounted for by planetary nebulae or is continuous mass outflow at slightly earlier evolutionary stages also important? Is the "coronal gas" (temperatures $\sim 10^5$K to 10^6K) in the Galactic Disk mainly due to Supernova Remnants or are "bubbles" blown by the stellar wind from OB-stars also significant? Do central stars of old, low-density planetary nebulae contribute much to ionization and are extended low-density HII regions ionized by O or B stars (Mezger 1978)? Much of the bulk kinetic energy in the motion of clouds comes from supernova remnant blast-waves, but what are the dynamic details when such a blast-wave proceeds through a clumpy medium or encounters a massive cloud-complex, as may be the case with IC443 (see Sect.8)?

Chemical abundances in the ISM <u>now</u> depend on the chemical evolution of the Galaxy at earlier times (Audouze and Tinsley 1976). Some time ago theorists had hoped that the stellar birthrate as a function of time and stellar mass has two simplifying properties: (a) it can be expressed as a simple product of a function of mass alone (the Initial Mass Function) and a function of time alone and (b) it is a smooth monotonically decreasing function of time. From different studies of external galaxies it is clear that both (a) and (b) are wrong: there are large-scale bursts of star formation and long quiescent periods instead of a smooth time-dependence; the mass to light ratio increases stongly in the outermost regions of galactic disks, indicating a preponderance of either very low or very high mass stars, which have long since produced supernova. The possibility of supernova explosions in the outermost regions of galaxies at early times would predict an appreciable iron abundance there (and X-ray spectroscopy has indicated the presence of iron in intergalactic gas). These complexities have led to the realization that one has to study chemical abundances (and their gradients) in external galaxies even if we wanted to understand only our own interstellar medium.

3. SOME OBVIOUS ADVANCES

The most obvious advance in our knowledge of the ISM would come from simply repeating the Copernicus observations of interstellar absorption lines with the very high resolution mode of the HRS, $\lambda/\Delta\lambda = 1.2\times10^5$ instead of 2.2×10^4. The corresponding increase in velocity resolution from 13.5 km s^{-1} to 2.5 km s^{-1} is of vital importance, especially for the predominantly neutral gas: The purely thermal velocity widths are small compared with 13.5 km s^{-1} and even observed total velocity widths (thermal plus turbulence plus rotation, etc.) of an individual absorption feature are usually $<$ 10 km s^{-1}, as shown both by observations in the visible of Na, I, say, (Hobbs 1969) and at 21 cm of HI (Dickey, Salpeter and Terzian 1979). On the other hand, the dispersion of velocities of "clouds" (absorption features) is just comparable with the Copernicus resolution - a frustrating coincidence. The resolution of 2.5 km s^{-1} is comparable to that used in modern 21 cm observations and one may wonder if the HRS will really give us new insights into the velocity structure of the ISM? However, the 21 cm absorption studies suffer from the fact that strong extragalactic background sources have to be used, which are sparsely dispersed over the sky. With the great sensitivity of the HRS one could study absorption towards a fairly large number of stars in adjacent regions of the sky (and at different distances). One may then be able to find out, for instance, whether turbulence (and/or rotation) velocities increase towards the spatial periphery of a cloud complex. Furthermore, one may even be able to separate these contributions from the true thermal velocity width and thereby get an estimate of kinetic temperatures (as distinct from excitation temperatures).

The high resolution of the HRS for absorption line studies will also make abundance determinations for ion species and molecules more reliable: The ambiguity between circumstellar and interstellar absorption lines should be lessened and line shapes will be obtained more directly. More important still is the greater sensitivity, which will enable the study of weak (as well as strong) lines for a given ion or molecule so that curve of growth difficulties can be overcome.

Another obvious, although very indirect, advance in our knowledge of the ISM will come from observations of stellar surfaces carried out for quite different purposes. Studies with the WFC and FOC will presumably extend luminosity functions for individual stars down to much fainter magnitudes, well below the main sequence turnoff in many systems. Spectroscopy will presumably lessen the uncertainties in chemical abundances in the surfaces of various stars. All this has no direct bearing on observations of the ISM, but it will put on a much firmer basis theoretical calculations on chemical evolution of galaxies and on the mass balance for the ISM (Tinsley and Larson 1977, Pagel 1979).

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

4. INTERSTELLAR ABSORPTION FOR HIGHLY REDDENED STARS

Absorption line measurements in the UV with Copernicus were possible for stars with interstellar reddening up to E(B-V) $\sim$ 0.5, with (E(B-V) $\sim$ 0.3 more typical (as for the most famous case sofar, Zeta Ophiuchi, Morton 1975, Snow and Meyers 1979). With the HRS, on the other hand, measurements will be possible up to E(B-V) $\sim$ 2, with E(B-V) $\sim$ 1 still quite economical in observing time. For stars in the galactic plane with the mean reddening law of $\sim$ 0.6mag/kpc in E(B-V) this improvement would only mean extending the range of the instrument from $\sim$ 500pc to $\sim$ 2kpc. For a "ubiquitous component" of the ISM, such as the coronal gas characterized by OVI absorption, this extension in range will make the separation between circumstellar and interstellar gas slightly more secure but will probably not have a major impact. However, the situation should be radically altered when the large interstellar reddening is due not to a large total pathlength but due to passage through a molecular cloud.

Typical values of extinction A_{UV} in the UV for $\lambda \lesssim 2200$ Å are roughly 2.5 times the visual extinction A_V and roughly 7.5 times E(B-V). Thus a cloud like the one in front of ζph has $A_{UV} \sim 2.5$, whereas the HRS will be easily able to penetrate a cloud with $A_{UV} \sim 7.5$, so that the diffuse field (for photon energies $\sim$ 10eV) is attenuated by a factor of order 10^{-3} rather than 10^{-1}. The balance between different ion, atomic and molecular species can be very sensitive to the value of such an attenuation factor since the UV photons mainly control ionization and dissociation. This is already demonstrated dramatically by the balance between atomic and molecular hydrogen (Savage et al 1977, Bohlin et al 1978): The sum N_{tot} of atomic column density N(HI) and of $2N(H_2)$ is close to $(6\times10^{21}cm^{-2})$ E(B-V) both for small and large reddening, but the ratio $N(H_2)/N(HI)$ changes from very small values for E(B-V) $\lesssim$ 0.1 to large values for E(B-V) appreciably above 0.1. For hydrogen, the rapid change of an abundance ratio occurs at fairly low values of E(B-V) and is expected theoretically (Hollenbach et al 1971, Myers et al 1978); similar, but more complex, changes in other species take place at larger values of E(B-V) which will only be accessible from the ST.

Fortunately there are a number of suitable reddened stars which are quite bright, V $\sim$ 8, such as one in the Monoceros Cloud with E(B-V)$\approx$0.8 and one in the ρ Oph cloud with E(B-V) $\simeq$ 1.1. Four hours of observing time per star with the very high resolution mode of the HRS will give details for about 70 absorption lines and abundances for more than 20 ion, atom and molecule species, mainly from the one dense cloud (or cloud complex) along the line of sight. These abundances will give information on the chemical reaction/ionization equilibrium in the cloud, but hopefully will also measure the gas-phase depletion factor for a number of elements. Furthermore, for a few molecular species one should see absorption lines originated from different rotational levels and from different isotopes, which will give information on temperature and density. For many of these clouds, eg. ρ Oph (Myers et al 1978), one already has information on many of the same molecular species from microwave emission. It is particularly exciting that a large millimeter-wave telescope, which can look for three different rotational transitions in CO in emission (λ = 2.6, 1.3 and 0.87 mm), should come into operation at about the same time as the ST which will see at least two rotational levels in CO in absorption. This will give not merely "one measurement of density and temperature" but enough redundancy to point out any serious discrepancies, which in turn should teach us something about the "real physics" involved.

As discussed in Sect. 3, the velocity structure of a cloud complex can be studied with a velocity resolution of 2.5km s^{-1}. It will be frustrating that even this excellent resolution is not quite good enough for molecular clouds where the temperature is low (<50K) and the velocity width can be less than the resolution if the cloud is quiescent. However, the real interest lies in <u>non</u>-quiescence: these clouds are at least the forerunners of gravitationally collapsing material which will form stars by fragmentation and the velocity structure might reveal (or at least hint at) shock speeds (Jura 1975) and/or turbulent velocities.

I want to enter my personal plea to observers for redundancy, rather than a broad coverage, when total observing time is limited - i.e. study a few objects thoroughly rather than all of them poorly. This includes using many lines and different observing techniques for one species in one direction in the sky, but also using as many stars as possible in or behind one cloud or cloud complex. As mentioned, this is still difficult to do in 21 cm HI absorption even with as large a telescope as the Arecibo dish; fortunately in this respect the ST mirror is "larger" than the Arecibo dish!

5. INTERSTELLAR DUST GRAINS

The observations discussed in Sects. 3 and 4, although planned for other purposes, will also give information on interstellar dust-grains in three different ways: (i) One indirect but important way is to study the gas-phase depletion of different elements from quantitative abundance measurements of different species, since atoms missing from the gas phase are presumably locked up in grains. It is particularly important to study how the depletion factors depend on (a) the chemical and crystallographic properties of the element (Field 1974, Salpeter 1977), (b) the velocity of the cloud or cloud-component (Shull et al 1977, Snow and Meyers 1979) and (c) the internal density and reddening E(B-V) of the cloud. Much theoretical work (Barlow and Silk 1977, Cowie 1978, Shull 1978, Draine and Salpeter 1979) has been done on this subject, but reliable observational data is badly needed on depletion factors. The increased absolute accuracy in abundance determinations, large number of molecular and ion species per element and the increased range in E(B-V) will help.

(ii) The <u>average</u> extinction curve of interstellar dust grains in the visible and UV is now known fairly well (Aannestad and Purcell 1973, Spitzer and Jenkins 1975), but the variations from case to case are not yet well understood. In particular, it is important to know how strongly the extinction peak near 2200Å (supposedly due to graphite) and the extinction rise towards 1000Å (supposedly due to very small grains) depend on the three parameters discussed under (i). Although the high spectral resolution of the HRS (or even the FOS) are hardly required for this work, extinction curves will become available over a much wider range of E(B-V). Correlation with infrared observations of the same cloud, such as the search for the 3.1μ ice-feature (Harris et al 1978) will also be of interest.

(iii) The ratio of grain scattering to grain absorption as a function of wavelength in the UV is of interest. I have not yet seen detailed plans for studying reflection nebulae in the UV with the WFC and FOC. However, the determination of abundance ratios for different ion stages of one element, or atom/molecule abundance ratios, in the gas phase (Sects.3 and 4) can give some indirect information: Since ionization and dissociation by UV photons has different threshold energies for different cases, one can (in principle) obtain the spectrum of the diffuse radiation field inside a particular cloud from measuring a set of different abundance ratios. Comparison with the diffuse radiation field in unreddened regions then gives estimates for the grain albedo. Some information of this kind has already been obtained (Jenkins and Shaya 1979) from abundance ratios for C, Na and K, but the ST should improve the situation.

So far only a little (Gehrels 1974) is known of the polarizing properties of the interstellar dust. The spectropolarimeter associated with the FOS (Harms 1979) should obtain direct information on this from stars with different amounts of reddening. One question of interest is the polarization of the 2200Å feature, since models for almost spherical graphite grains predict little polarization.

6. OUR IMMEDIATE NEIGHBORHOOD

The high sensitivity of the ST will mainly be used to increase distances over which observations can be made, but there is also one application to explore the ISM at smaller distances from us than has been possible in the past: For absorption studies in the UV with less sensitive instruments one requires stars which are bright in the UV, i.e. the rare O and B-stars; thus the nearest star observed with Copernicus is about 65pc away. White dwarfs and late-type main sequence stars, on the other hand, are faint in the UV but very common; there are over 20 K-type main sequence stars within 5pc and over 20 white dwarfs within 15pc. Fortunately the late-type main sequence stars emit some chromospheric Lyα and the emission spectrum in the UV of some white dwarfs (especially for type DA) has already been measured with the IUE (Greenstein and Oke 1979).

To be more precise, Copernicus and IUE are sufficiently sensitive to measure the emission spectrum of K-stars and white dwarfs in the UV

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

and some absorption studies have already been attempted (e.g. for the K2V star ε Eri at 3.3pc, McClintock et al 1976). However, the combined sensitivity and high spectral resolution ($\lambda/\Delta\lambda = 1.2\times10^5$) of the HRS will be required to disentangle the very faint (but narrow) interstellar absorption lines from the complex spectrum (with broader spectral features) of the star itself. Only a few minutes per white dwarf will be required to loof for CI, CII, NI and OI absorption lines at wavelengths between 1200 and 1400Å. Similarly, about 10 minutes per K-star will be required to obtain HI column density and velocity distribution from Lyα absorption.

This study of the nearby ISM is made more interesting and also more difficult by the fact that the HI density in our vicinity is quite low compared with the average density in the galactic disk. Observations on backscattered solar Lyα radiation (Fahr 1974) and some stellar observations (Dupree 1975) had already indicated this, but it is still not clear whether hydrogen densities are typically of order 0.02 cm^{-3} or 0.2 cm^{-3}. A study of a few dozen stars with the HRS will only require a few hours in total and yet should give us a lot of information about the nearby hydrogen distribution. In terms of "value per observing time" I consider this a very high priority project.

7. HIGH VELOCITY CLOUDS; CORONAL GAS IN A GALACTIC HALO

Twenty-one centimeter studies of neutral hydrogen in emission are very extensive; "intermediate-velocity clouds" ($20\mathrm{km\ s^{-1}} < |v| < 60\ \mathrm{km\ s^{-1}}$) are reasonably common, "high velocity clouds" ($|v| > 60\ \mathrm{km\ s^{-1}}$) are rather rare but fairly well-mapped. The physical nature of these clouds is mostly a mystery (except for some which are probably connected with very old supernova remnants and others at low galactic latitudes which are probably part of an outer, warped galactic disk). The emission data (Verschuur 1975) can help little on the two important observational questions of temperature and distance for such clouds.

Absorption studies at 21cm can, in principle, measure the temperature of the neutral hydrogen. Some measurements of this kind have been and will be made (Payne et al 1978), but even the Arecibo dish is on the borderline of being too small for this job. In particular, I am not too optimistic for Arecibo absorption data for clouds which are both at very high galactic latitudes and at high velocities, which are the most controversial (furthermore, 21cm studies use extragalactic background sources which are much more distant than these clouds, no matter which model for them is right). Fortunately there are many blue stars at high galactic latitudes with $m_V \sim 7$ to 10, situated in the nearby Galactic halo (1 or 2 kpc away, say). For such stars in the direction of high velocity clouds, the usual HRS absorption line studies will easily show various ion species of C, N, O and Si if the cloud is closer than the star. This is predicted on some models for such clouds, but not on others, and the absence or presence of absorption will provide one clue to the controversy. If present, the absorption lines will also give

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

chemical abundances and ionization conditions which are also uncertain. Clouds at somewhat lower velocities and latitudes are more plentiful and less spectacular but are not fully understood either and should not be neglected: Some UV absorption results are already available (Shull 1977, Cowie and York 1978), but the HRS can do much more and it would be particularly useful if the same cloud could be studied with the HRS and at Arecibo.

Not only the nature of high-velocity neutral gas is controversial at the moment, but so is the presence in our Galactic halo of coronal gas, which was already predicted by Shklovsky (1952) and Spitzer (1956). Absorption lines in the wavelength region 1200Å to 1600Å of CIV, NV and Si IV should be characteristic of such coronal material. Suitable background sources at high galactic latitudes should be individual O and B supergiants in the Magellenic Clouds, the cores of bright Seyfert galaxies and even 3C273. Some coronal gas in our halo (using stars in the LMC) has already been detected with the IUE (Savage and de Boer 1979), but the sensitivity and spectral resolution ($\lambda/\Delta\lambda = 1.2\times10^4$) of the IUE is marginal for this work. Even the lower spectral resolution of HRS is (slightly) better than the highest resolution on IUE (and the sensitivity enormously greater), so these observations should become relatively simple.

8. PLANETARY NEBULAE AND SUPERNOVA REMNANTS; STATISTICS AND ABUNDANCES

The physics of emission nebulae, including planetary nebulae (PN), has been discussed by Osterbrock. Besides being of interest in their own right, planetary nebulae are important for returning mass into the ISM and their central stars may be important for providing ionizing photons. Recent estimates (Pottash et al 1978) of the ionizing flux from a central star are low and these stars may not compete effectively with OB-stars, but more data are needed. Although the ST does not observe photons beyond 13.6 eV directly, observing the emission spectrum of a star in the UV almost up to the Lyman edge will lead to more reliable stellar atmosphere models which in turn can predict the flux of ionizing photons. These measurements can be done most systematically for PN in the Magellanic Clouds where distances are known accurately; the FOS will be suitable for these central stars with $m_V \sim 16$ to 22. About 20 PN in our own Galaxy have central stars with $m_V < 12$; these can be observed with the HRS to obtain absorption lines from each star's own nebula.

For establishing the overall rate of occurence of PN reliable distances are important and for that purpose PN in the Magellanic Clouds (or other external galaxies) are useful. In order to draw reliable conclusions about the PN distance scale in our own Galaxy from external data one has to understand the variation of PN statistics with Hubble type and therefore one also needs data on the more distant members of the Local Group, such as Andromeda and its companions. Identification of extragalactic PN from groundbased telescopes has already been achieved (Ford 1978, Jacoby 1978, Webster 1978), especially using onband/off-band filter photography on nebular emission lines such as [OIII]λ5077. However, most PN even in the Magellanic Clouds have an angular size less than 2" and cannot be resolved reliably from groundbased photographs. The FOC and WFC, on the other hand (D'Odorico et al 1979) will be able to resolve all PN in the Magellanic Clouds (and even display some finestructure), which should pin down individual ages and overall occurence rates fairly well. For the more distant members of the Local Group the PN sizes should range up to about 0.2", so that only some can be resolved but many can be detected. Hβ observations of internal finestructure (at least for the nearer PN) should provide filling factors and, hopefully, masses (as well as ages) of individual nebulae will be obtained more reliably.

With supernova remnants (SNR) one also will be striving for statistics from external galaxies with known distances, on the one hand, and more physical details for Galactic SCR on the other hand. There are already some groundbased observations of SNR in the Local Group (Danziger et al 1979, Dopita 1979), but one is limited by sensitivity or resolution. Searches with the WFC (using Hα or [SII] filters) should do much better and the FOC could reveal internal structure (Danziger 1979). For the nearby Galactic SNR the WFC can of course give finer spatial structure but there is even a possibility of measuring proper motion (up to 0.1"/year for Vela or Cygnus). For a few Galactic SNR one can even find an O star behind the remnant, so that one can observe absorption lines from the path through the remnant. One example is HD254755 behind IC443, a moderately young SNR (Malina et al 1976) which is a particularly interesting case: Besides the usual X-ray emission for a SNR (Winkler and Clark 1974), gas at about 10^6K has also been observed recently (Woodgate et al 1974). Cool gas, including neutral atomic hydrogen 21cm emission (DeNoyer 1978) and even some molecules, is also associated with IC443 in a less direct manner. I again would like to urge observers with different techniques to select a <u>few</u> out of many (including IC443) for really intensive study - to provide the theorists with redundancy and discrepancies!

The determination of chemical abundances in the gas phase is of course an important incentive in the study of PN and SNR, as well as HII regions (Perinotto and Renzini 1979, Pagel 1979). For SNR (and their associated neutral intermediate-velocity clouds) an interesting question is whether destruction by sputtering of the dust grains lessens the gas-phase depletion (Jenkins et al 1976). For PN a mundane but important advance will be obtaining precision values for abundances of C, N and O: Abundance ratios of these species depend on the birthrate function for the stars from which the ISM was enriched (Tinsley and Larson 1977, Pagel 1979). Another important clue to the chemical evolution of galaxies lies in radial abundance gradients in galactic disks of various Hubble types. Groundbased observations (Searle 1971, Hawley 1978, James 1979) suggest such gradients for regular spirals but not for irregular galaxies such as the Magellanic Clouds. However, excitation conditions and dust/gas ratios are likely to vary with distance from a galaxy cen-

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

ter, as well as abundances themselves. To disentangle these various effects it is imperative to be able to measure as many different lines of different ion species as possible and the ST will surely help here.

The ISM is complex not merely in its region-to-region variations, but also in the coexistence of many components in one region of space (or at least one line of sight). I already mentioned the large range of temperatures associated with the supernova remnant IC443. For the Orion complex one not only has the constrast between the ionized region (Pankonin et al 1979) and the molecular cloud, but even for the molecular cloud alone one has the contrast between presumed thermal Doppler velocities of less than $1 kms^{-1}$ and some observed velocity structure up to $100 kms^{-1}$ (Nadeau and Geballe 1979). Coordinating ST observations with those on the VLA and the mm-wave telescope will be challenging, due to the complexity of the medium and the large increase in resolution of all three instruments (coupled with the fact that ISM observations will not have particularly high priority for the VLA). I also want to endorse Osterbrock's plea for a concerted effort on theoretical model calculations - redundancy in observations must be coupled with sophisticated data analysis.

This work was supported in part by NSF under Grant AST 78-20708.

REFERENCES

Aannestad, P. A. and Purcell, E. M.: 1973, Ann. Rev. Astron. Astrophys. 11, pp. 309.
Audouze, J. and Tinsley, B. M.: 1976, Ann. Rev. Astron. Astrophys. 14, pp. 43.
Barlow, M. J. and Silk, J.: 1977, Ap. J. 211, pp. L83.
Bohlin, R. C., Savage, B. D. and Drake, J. F.: 1978, Ap. J. 224, pp. 132.
Brandt, J. C. et al: 1977, A High Resolution Spectrograph for the Space Telescope, GSFC proposal to NASA, HRS-680-77-01.
Chevalier, R. A.: 1977, Ann. Rev. Astron. Astrophys. 15, pp. 175.
Cowie, L. L.: 1978, Ap. J. 225, pp. 887.
Cowie, L. L. and York, D. G.: 1978, Ap. J. 223, pp. 876.
Dalgarno, A. and McCray, R. A.: 1972, Ann. Rev. Astron. Astrophys. 10, pp. 375.
Danziger, I. J.: 1979, in Astronomical Uses of the ST (ed. Machetto, Pacini and Tarengini), ESA/ESO.
Danziger, I. J., Murdin, P. G., Clark, D. H. and D'Odorico, S.: 1979, M.N.R.A.S. 186, pp. 555.
DeNoyer, L. K.: 1978, M.N.R.A.S. 183, pp. 187.
Dickey, J. M., Salpeter, E. E. and Terzian, Y.: 1979, Ap. J. 228, pp. 465.
D'Odorico, S., Perinotto, M. and Benvenuto, P.: 1979, in Astronomical Uses of the ST (ed. Machetto, Pacini and Tarengini), ESA/ESO.
Dopita, M. A.: 1979, Ap. J. Supplem. 40, pp. 455.
Draine, B. T. and Salpeter, E. E.: 1979, Ap. J. 231, pp. 438.
Dupree, A. K.: 1975, Ap. J. 200, L27.

Fahr, H. J.: 1974, Space Sci. Rev. 15, pp. 483.
Field, G.: 1974, Ap. J. 187, pp. 453.
Ford, H. C. 1978, in Planetary Nebulae (ed. Y. Terzian) D. Reidel, Dordrecht.
Gehrels, T.: 1974, Ap. J. 79, pp. 591.
Greenstein, J. L. and Oke, J. B.: 1979, Ap. J. 229, L141.
Harms, R., Bartko, F., Beaver, E. and Ford, H.: 1977, UC/MMC Faint Object Spectrograph for the Space Telescope, U. C. Proposal to NASA.
Harms, R.: 1979, UCSD Report FOS-UCSD-SC-01.
Harris, D. H., Woolf, N. J. and Rieke, G. H.: 1979, Ap. J. 226, pp. 829.
Hawley, S. A.: 1978, Ap. J. 224, pp. 417.
Heiles, C.: 1976, Ap. J. 204, pp. 379.
Hobbs, L.: 1969, Ap. J. 157, pp. 135.
Hollenbach, D., Werner, M. W. and Salpeter, E. E.: 1971, Ap. J. 163, pp. 165.
Jacoby, G. H.: 1978, Ap. J. 226, pp. 540.
Janes, K. A.: 1979, Ap. J. Supplem. 39, pp. 135.
Jenkins, E. B.: 1978, Ap. J. 220, pp. 107.
Jenkins, E. B., Silk, J. and Wallerstein, G.: 1976, Ap. J. Supplem 32, pp. 681.
Jenkins, E. B. and Shaya, E. J.: 1979, Ap. J. 231, pp. 55.
Jura, N.: 1975, Ap. J. 197, pp. 581.
Malina, R., Lampton, M. and Bowyer, S.: 1976, Ap. J. 207, pp. 894.
McClintock, W., Henry, R. C. and Moos, H. W.: 1976, Ap. J. 204, pp. L103.
McCray, R. and Snow, T. P.: 1979, Ann. Rev. Astron. Astrophys. 17 (in press).
Morton, D. C.: 1975, Ap. J. 197, pp. 85.
Mezger, P. G.: 1978, Astron. Astrophys. 70, pp. 565.
Myers, P. C. et al: 1978, Ap. J. 220, pp. 864.
Nadeau, D. and Geballe, T. R.: 1979, Ap. J. 230, pp. L169.
Osterbrock, D. E.: 1974, Astrophysics and Gaseous Nebulae, Freeman Publ. San Francisco.
Pagel, B. E.: 1979, in Astronomical Uses of the ST (ed. Machetto, Pacini and Tarengini), ESA/ESO.
Pankonin, V., Walmsley, C. M. and Harwit, M.: 1979, Astron. Astrophys., 75, pp. 34.
Payne, H. E., Dickey, J. M., Salpeter, E. E., Terzian, Y.: 1978, Ap. J., 221, L95.
Perinotto, M. and Renzini, A.: 1979, in Astronomical Uses of the ST (ed. Machetto, Pacini and Tarengini), ESA/ESO.
Pottash, S. R., Wesselius, P. R., Wu, C. C., Fieten, H. and v. Duinen, R. J.: 1978, Asto. Ap. 62, pp. 95.
Salpeter, E. E.: 1977, Ann. Rev. Astron. Astrophys. 15, pp. 267.
Salpeter, E. E.: 1979, in Large Scale Charecteristics of the Galaxy (IAU Symp.84, ed. Bu. Burton), Reidel, Dordrecht.
Savage, B. D., Bohlin, R. C., Drake, J. K., and Budich, W.: 1977, Ap. J. 216, pp. 291.
Savage, B. D. and de Boer, K. S.: 1979, Ap. J. 230, L77.
Searle, C. L.: 1971, Ap. J. 168, 327.
Shklovsky, I. S.: 1952, Soviet Astron. - AJ. 29, pp. 418.
Shull, J. M.: 1977, Ap. J. 216, pp. 414.

Shull, J. M.: 1978, Ap. J. 226, pp. 858.
Shull, J. M., York, D. G. and Hobbs, L. M.: 1977, Ap. J. 211, pp. L139.
Snow, T. P. and Meyers, K. A.: 1979, Ap. J. 229, pp. 545.
Solomon, P. M., Saunders, D. B. and Scoville, N. Z.: 1979, in Large Scale Characteristics of the Galaxy (IAU Symp.84, ed. B. Burton) Reidel, Dordrecht.
Spitzer, L.: 1956, Ap. J. 124, pp. 20.
Spitzer, L.: 1978, Physical Processes in the Interstellar Medium, J. Wiley, New York.
Spitzer, L. and Jenkins, E. B.: 1975, Ann. Rev. Astron. Astrophys. 13, pp. 133.
Tinsley, B. M. and Larson, R. B.: 1977, The Evolution of Galaxies and Stellar Populations, Yale University.
Verschuur, G. L.: Ann. Rev. Astron. Astrophys. 13, pp. 257.
Webster, B. L.: 1978, in Planetary Nebulae (ed. Y. Terzian) D. Reidel, Dordrecht.
Winkler, P. F. and Clark, G. W.: 1974, Ap. J. 191, pp. L67
Woodgate, B. E., Lucke, R. L. and Socker, D. G.: 1979, Ap. J. 229, pp. L121.

DISCUSSION

Jura (Discussion leader): The prime instrument for study of the interstellar gas is the High Resolution Spectrograph. Copernicus was able to detect absorption lines of equivalent width 1 mÅ. As compared with Copernicus, ST provides two advantages. First, lines of equivalent width 0.1 mÅ can be studied which means that very weak lines can be measured for which there are no corrections for optical depth in radiation transfer. Second, observations can be made over a very much larger dynamic range. Let me give two examples of the types of study which will be possible. From observations with Copernicus, it has been shown that there is a correlation of colour excess with H_2 column density in the solar neighbourhood. There is some residual scatter about this relation and it is important to know if this reflects a real scatter in the colour excesses or if it is due to poor estimates of the colour excesses. If the former is the case, it means that there are real non-uniformities in the abundances and this is important in relation to studies of abundance gradients in the Galaxy. There is some evidence that the D/H ratio is also variable and this may be closely related to variations in other element abundances as measured by the colour excesses. Very much more accurate data on this correlation will be obtained with the HRS. The second example concerns the microphysics of the interstellar medium. Hydrogen atoms stick to the surface of grains and are catalysed into H_2 molecules. What happens, for example, to an oxygen atom when it hits a grain? If it sticks, the atomic oxygen abundance is depleted in the cloud. If it comes off in molecular form, as OH, H_2O or CO for example, searches can be made for all three species and the relative efficiencies of molecule formation for hydrogen and oxygen atoms can be measured directly. The HRS will prove a very powerful tool for the study of such problems.

Field: How can you distinguish molecules formed on grains from those formed in gas-phase reactions?

Jura: You can look in the direction of regions containing very low abundances of molecular hydrogen and then there will be very little ion-molecule chemistry going on.

Snow: There are also molecular species which only form in endothermic gas phase reactions and these are again good candidates for formation on grains.

Ostriker: I have two comments on Dr. Salpeter's lecture. First, it is surprising to me how constant the initial stellar mass function may be. The existence of dark matter in the halo should not be used as an argument one way or another because we do not know what it is and it may not have anything to do with star formation. Second, in models of the interstellar gas in which hot and cold gas coexist, there are observa-

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

tional tests. In particular, if there are hot and cold regions with intermediate temperature gas in between, there should exist velocity correlations i.e. the intermediate gas should move at the same velocity as the cold gas.

van de Hulst: Dr. Salpeter mentioned in his talk that, of course, there will be a continuum of states of the interstellar gas. Does this mean that you believe there will not be distinct phases?

Salpeter: Observationally I merely note that, whenever an observing technique has become available which is sensitive to a particular temperature range, a positive detection followed. Theoretically, one can certainly get the coexistence of two phases, but the numerical value of temperature depends on the pressure so that even a given phase will have different temperatures at different places.

Savage: ST can be used to study the distribution of hot gas in the galactic halo. We have obtained spectra of stars in the Magellanic Clouds in the ultraviolet waveband using IUE. The profiles of CIV and SiIV show gas in absorption local to our own Galaxy and to the Magellanic Cloud. The strong Galactic features extend to positive velocities of about 150 km s^{-1}. If this gas corotates with the disc of the galaxy, there must be a halo of hot gas around our Galaxy extending up to 8 kpc from the galactic plane.

The present data are rather noisy and the minimum detectable equivalent width is $\sim$ 40 mÅ which puts it on the flat part of the curve of growth which limits the analysis. With ST, we will obtain the following advantages: (i) The data will be of very high precision enabling detailed studies of the line profiles to be made. In particular equivalent widths very much less than 30 mÅ may be readily detected. (ii) Some tantalising features of the spectra are barely resolved and the higher spectral resolving power of ST will enable these features to be studied. (iii) The assumption that the hot gas corotates with the disc may be checked by making observations in a number of different directions. This is not possible with IUE because there are too few bright stars. With the HRS, it will be possible to use fainter objects such as quasars, Seyfert nuclei, possibly the nuclei of galaxies and globular clusters.

York: With ST, it will be possible to measure the equivalent widths of absorption lines as weak as 0.1 mÅ for stars brighter than $m_V = 5$. These weak features will be observable in components of hydrogen column density 3 x 10^{19} cm^{-2}. Studies of Lyman-α in the direction of Orion stars have indicated column density 2-3 x 10^{20} cm^{-2} but studies of the sodium lines suggest that this consists of a number of individual components with column densities $\sim$ 2-3 x 10^{19} cm^{-2}. The main problem is that we do not know hydrogen column densities as a function of velocity because of the great width of the Lyman-α and Lyman-β lines. However,

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

there are other elements which can be studied and which together lead to precise determinations of physical conditions. In particular, "volatile" elements such as CII, BII, BeII, NI, OI, SII, PII and ZnII should be present with Solar abundances in almost any cloud. With the high resolution of ST, b-values can be measured to $1\frac{1}{2}$-2 km s^{-1} and it is not unreasonable to expect to measure temperatures of HI regions accurately down to 3000 K. To go cooler, T $\sim$ 500 K, doublet techniques would have to be used. This should be reasonably precise for ST observations because we do not have to worry about blends.

A problem is that even along the simplest line of sight which shows only a single line with Copernicus, there may be as many as nine components according to current theories. We may expect a single cloud to have low velocity HI, low velocity HII, shocks at the edge giving high velocity HII and cooling gas behind the shock producing high velocity HI, and so on. It will be difficult to separate these out. However, using nitrogen and oxygen, the position of the neutral component can be found. Inside these neutral clouds, the warm edges may be separated from the cooler central regions. Most important is the determination of the neutral hydrogen distribution in the region. This is now possible with ST. From studies of the species listed above, we can derive all the important physical parameters, volume densities, electron densities, temperature, etc. It will be particularly important to study the formation rates of molecular hydrogen in these clouds.

Jenkins: It is important to measure the pressure in HI regions, its mean value, variations from the mean and their causes and the study of departures from equilibrium. The pressure is an elusive quantity to measure and can only be studied by indirect methods. For example, the relative abundances of neutral and ionised species can be used to find the pressure from ionisation equilibrium calculations if the photoionisation rate is known. This method is, however, sensitive to assumptions about the ionisation rate. Alternatively, the H_2 rotational popolations can be used to provide estimates of pressures but these are complicated by details of the radiative cascade and the initial distribution of H_2 when it comes off grains.

I want to emphasise the importance of studying spectroscopically the relative populations of atoms of different stages of fine-structure excitation from the J-level splitting of the ground state. CI is particularly important in these studies since it is almost always found in HI regions. Except at very low pressures, the dominant excitation and de-excitation processes are collisional. A particular advantage of CI is that the excitation cross-section by atomic and molecular hydrogen is more or less the same so that the total excitation only depends upon the total amount of hydrogen present. CI is not strongly depleted in HI regions. In addition, the energy levels are close together so that the Boltzmann factor is not too important. Carbon has electronic levels

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press

with three fine structure states which respond differently in different pressure regimes. It is therefore possible to get information not only about mean values but also about the distribution of pressure from a single observation. Many of these multiples are of different line strength and therefore one can use those of appropriate strength to avoid uncertain assumptions about the curves of growth.

Examples of goals for ST using the High Resolution Spectrograph are:
(i) Study of distant stars, especially along lines of sight through spiral arms to test density wave theory of spiral structure.
(ii) Studies of heavily reddened clouds to determine precise pressure enhancements and the dynamical evolution of the system.
(iii) The differences in velocity dispersion between excited and unexcited lines giving better indication of structure in the clouds.
(iv) Study of negative velocity material being compressed and ejected from OB association complexes
(v) Extending Copernicus observations in an unbiased way through the study of faint objects.

Snow: A great deal of information about interstellar clouds can be derived in cases where radio and optical techniques can be applied to the same cloud. Currently there are few clouds where such overlap is possible, because of the low sensitivity of existing ultraviolet spectrographs. With the ST there will not be a great number of regions dense enough to produce complex millimeter molecular spectra and still be transparent enough for optical absorption-line measurements to be made, but certainly some progress in this direction will be achieved. There will be benefits for both the radio and optical observers, including the use of optical techniques to derive such parameters as atomic abundances, radiation field intensities, abundances of some molecular species that have no millimeter-wave spectra, and the nature of the extinction curve within dense clouds, all of interest to the radio observers. For their part, the radio data provide high velocity resolution so that the velocity dispersion of the gas will be measured directly, greatly reducing uncertainties in analyzing the optical data. For the first time we will have information on physical conditions in dense clouds where complex chemical processes have taken place.

Hemenway: As an astrometrist, I am trying to think of ways to help you. Apparently we see spatial structure in the interstellar medium at all spatial resolutions. One could expect to find filamentary structure at the resolution of the ST, i.e. $\theta \sim 0.1$ arcsec. If a star were moving through or behind a cloud, say with a velocity of 50 km s^{-1} relative to the cloud, perpendicular to the line of sight, then it would pass completely behind (through) a 100 pc filament in 10 years. By doing time dependent ($\tau \gtrsim$ 1 year) spectroscopy on the interstellar lines, one could study the microstructure of the filament. One must observe not only the time dependent spectrum, but also the relative motion of the star and filament, and perhaps do accurate simultaneous photometry.

https://doi.org/10.1017/S0252921100110954 Published online by Cambridge University Press