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FUTURE STUDIES OF THE LOCAL INTERSTELLAR MEDIUM WITH SPACE TELESCOPE AND COLUMBUS

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ABSTRACT

The spectrographs aboard Space Telescope and Columbus will provide important new information about the interstellar medium in the immediate vicinity of the sun. The Space Telescope high resolution spectrograph (HRS) will produce resolutions, $\lambda/\Delta\lambda$, of about 18,000 and 70,000 with high sensitivity between 1200 and 3200 A and greatly reduced sensitivity between 1060 and 1200 A. The highest resolution is adequate to define the multi-component nature of interstellar absorption lines and to measure thermal line widths exceeding 3 km s^{-1}. The Columbus mission is in the planning stages. However, it is likely that the spacecraft will contain spectrographs capable of resolutions of 3×10^4 between 912 and 1200 A and 500 between 100 and 900 A. In the longer wavelength region, the very important lines of O VI, S VI, H_2, H I, and D I are available for study. In the short wavelength region, lines of He I and II, are observable. If the $3x10^4$ resolution spectrograph can provide extended wavelength coverage to 770 A, lines of Ne VIII which are expected from $8x10^5$ K gas are accessible. Astronomers using the ST HRS and Columbus spectrographs will be able to study a wide range of problems relating to cold, warm, and hot gas in the local ISM. Some of the most important observing projects are described.

INTRODUCTION

We have heard from the many papers presented at this meeting that instruments in space are providing important new insights about the nature of the local ISM. The results from IRAS, Copernicus, IUE, Voyager, and the various EUV and soft X-ray programs have revealed a region of our galaxy containing warm and hot gas with embedded clouds of cooler gas and dust. This local region has been studied through its emission and/or absorption characteristics in all parts of the electromagnetic spectrum. Advanced space facilities in the future will help answer many current questions about our local interstellar environment and will undoubtedly raise many new questions.

Table 1 lists missions that are either being built or are in the planning stages that might provide new information about the local ISM. This list does not include the many small instruments that are being designed for Shuttle sortie missions. For example, one such instrument is discussed by C. Martin and S. Bowyer in these proceedings. Another is the ASTRO mission to be flown on the Shuttle starting in 1986 with a complement of three UV telescopes. The major facilities from Table 1 for local ISM studies will likely be the Space Telescope High Resolution Spectrograph (HRS) and the Columbus mission. Most of my discussion will concern these two instruments. However, many of the other instruments listed in Table 1 may provide important new data about the

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local ISM. Some of these possibilities are briefly described in the notes to Table 1. For missions such as Columbus, Starlab, AXAF, and SIRTF, the complement of local plane instruments has only been discussed in the broadest terms. I would hope that the final instrument configuration for each of these missions would contain an instrument suitable for studying our local interstellar environment.

TABLE 1: FUTURE MISSIONS

Mission	Aperture	Spectroscopic Capability		Approximate Launch Date
		Wavelength Range (A)	Resolution ($\lambda/\Delta\lambda$)	
ST-HRS	2.4^m	1175-3200 1175-3200 1175-1800	$7x10^4$ $2x10^4$ $2x10^3$	1986
EUVE	0.4^m	100-900 100-900	3 $1x10^2$	1987
COLUMBUS	$\lesssim 1^m$	900-1200 1200-2000 100-900 900-2000	$3x10^4$ $1x10^4$ $5x10^2$ $2x10^3$	1990's
STARLAB	1^m	1150-3200	$1x10^5$	1990's
AXAF	1.2^m	$\lesssim$ 100	not determined	1990's
SIRTF	1^m	$\gtrsim$30,000	not determined	1990's

EUVE (Extreme UV Explorer) - This instrument will obtain broad band photometry for a large number of sources between 100 and 1000 A. For the hotter stars detected, it may be possible to estimate the strength of the continuous H I absorption and thereby further delineate the 3 dimensional structure of local neutral hydrogen. The EUVE spectrometer will have a resolution of 10^2. This instrument will provide interstellar He I and He II absorption line information for the hotter white dwarfs.

STARLAB - Although primarily intended for high resolution imaging, Starlab may have spectroscopic modes. An echelle spectrograph operating at λ>1150 A with $\lambda/\Delta\lambda \sim 10^5$ has been considered. With a large area detector, spectra with nearly complete wavelength coverage could be obtained in two integrations. At the highest resolution the ST-HRS Digicons can only record ~5 to 10 A of the spectrum per integration. With Starlab most of the programs considered for the ST-HRS could be pursued, but with greater efficiency.

AXAF (Advanced X-Ray Astronomy Facility) - This 1.2 m facility will very likely have spectroscopic capabilities at wavelengths up to 100 or 200 A. If the resolution is adequate ($\lambda/\Delta\lambda \sim 3x10^3$) interstellar lines produced by the highly ionized atoms of the hot local ISM should be detectable toward sources with adequate continuum fluxes near 100 A. It would be very important to make sure AXAF and Columbus overlap in their wavelength coverage.

SIRTF (Space Infrared Telescope Facility) - This instrument will operate in the IR at λ>30,000 A. It will likely have a variety of spectroscopic modes and could be used to probe absorption and/or emission from molecules in very local clouds. Of particular importance would be the ability to study H_2 emission near 28 μm.

THE SPACE TELESCOPE HIGH RESOLUTION SPECTROGRAPH

The High Resolution Spectrograph (HRS) is a pulse-counting multichannel ultraviolet spectrograph developed for flight on the Space Telescope. Its design and operation are described by Brandt et al. (1979, 1981, 1982). The HRS was developed by the NASA Goddard Space Flight Center with Ball Aerospace systems Division as the prime contractor and scientific direction by the Principal Investigator (John C. Brandt) and members of the HRS Investigation Definition Team (see Brandt et al. 1979).

The HRS optical system is illustrated in Figure 1. The instrument consists of seven grating spectrometer modes and 4 imaging acquisition modes within a package 0.9 x 0.9 x 2.2 meters and with a weight of 700 pounds. The grating and acquisition modes are divided into two groups, side 1 and side 2, each with its own photon counting diode array (Digicon). Side one is designed to work from 1050 to 1700 A and side two from 1150 to 3200 A. The gratings are mounted on a rotating carrousel.

The HRS has three spectral resolution modes, sometimes characterized by nominal values R = wavelength/(line width) = 100,000, 20,000, and 2,000. They are referred to here as the high, medium, and low resolution modes, respectively. Measurements of the widths (FWHM) of emission lines in the spectrum of the internal Pt-Ne lamp indicate actual resolving powers as given in Table 2. Some of these numbers should increase as the result of instrumental modifications being made during the spring and summer of 1984.

TABLE 2: SPECTRAL RANGE AND RESOLVING POWER OF THE HRS

Resolution Mode	Grating Number	Spectral Range	R = λ/FWHM
Low	G5	1060-1800 A	1,500-2,500
Medium	G1	1060-1800	15,000-26,000
"	G2	1160-2100	15,000-31,000
"	G3	1600-2300	18,000-28,000
"	G4	2200 3200	13,000-21,000
High	G6	1060-1750	60,000-90,000
"	G7	1700-3200	70,000-100,000

Figure 2 illustrates the sensitivity of the various modes. The detector on side 1 has a LiF window which will permit observations down to approximately 1060 A. However, the sensitivity between 1060 and 1200 A will be very low since all the reflecting optical components have MgF overcoats.

The HRS has two entrance apertures. One subtends a 2 arcsec square, the other a 0.25 arcsec square. The larger slit will normally be used for target acquisition, while the smaller slit will be used for observations that require high spectral purity or high spatial resolution (e.g., isolating one star in a group).

The HRS has two redundant platinum-neon hollow cathode lamps which provide a reference spectrum for wavelength calibration. In the high resolution mode, wavelength calibrations with a precision of about 1 km s^{-1} should be possible.

In orbit the primary sources for photometric calibration will be standard stars. However, internal Xenon lamps are used for "flat field" calibrations to map irregularities in the photocathode response and to locate the edges of the photocathode mask for geometric calibrations. With special observing techniques to reduce the effects of photocathode nonuniformities, it should be possible to detect interstellar spectral features less than one percent in depth.

Two major reasons for selecting the digicon as the HRS detector were its pulse-counting capability and its wide dynamic range. During laboratory calibration, it was found that input count rates as high as 150,000 counts/sec/diode can be accurately measured. With a measured dark count of 0.001 counts/sec/diode, this yields a dynamic range of 150 million. The digicon detector should make it possible to obtain very accurate line profiles of interstellar absorption lines.

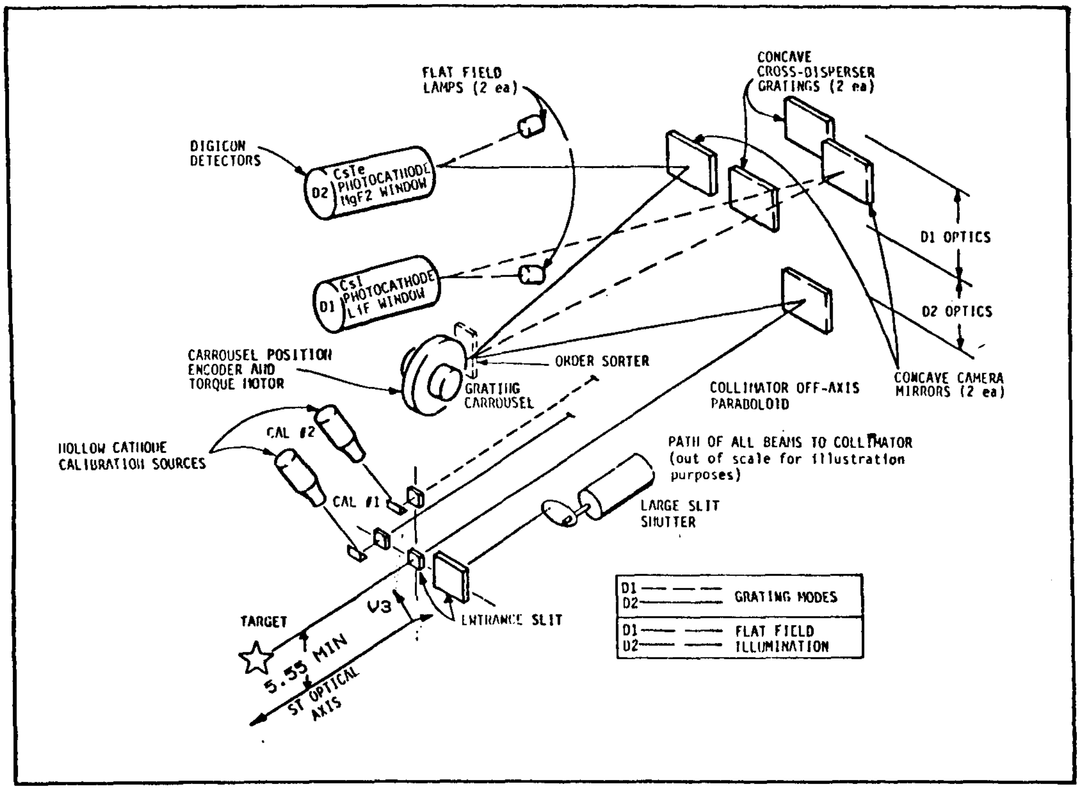

Fig. 1
HRS
Optical
System

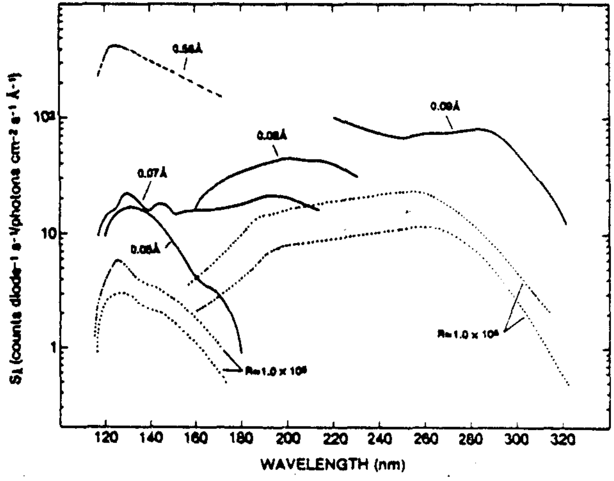

Fig. 2
Combined
HRS
and
Telescope
Sensitivity

THE COLUMBUS MISSION

In July 1983 the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) co-sponsored a workshop at Annapolis, Maryland on a possible joint ultraviolet astronomical mission. In setting up this workshop the two agencies recognized that several proposals and studies for such a mission were in circulation. These included the April 1983 report of a NASA working group for the Far Ultraviolet Spectroscopic Explorer (FUSE), a proposal to the UK Science Research and Engineering Council for an Ultraviolet Space Observatory, and a proposal to ESA for the Magellan mission. All three of these proposals or studies involved an instrument optimized for high resolution spectroscopy in the 900 to 1200 A region. However, the various proposed missions had different secondary goals in terms of wavelength regions and resolutions. Furthermore, the various instrument concepts for the primary science goals were very different. The intent of the July 1983 workshhop was to bring together European and American scientists and engineers to discuss the characteristics of a satellite that could be jointly funded. To avoid confusion, it was decided by the conference participants to call the possible joint mission "Columbus". As a result of the success of the first international Columbus workshop, a second workshop was held in Rome, Italy in May 1984. the Columbus mission as described below represents the outcome of the 1983 and 1984 workshops.

The scientific objectives of Columbus require a primary telescope feeding two or more spectrographs. For the primary telescope a one meter class grazing incidence design seems best able to support the science goals. High throughput for $\lambda \simeq 100$ A is possible with grazing incidence angles of about 10 degrees. Such a grazing incidence telescope is easier to build than one with the smaller graze angles required for the X-ray region. The actual telescope aperture will depend on cost constraints and whether the orbit is a low orbit or a geosynchronous orbit. The complex cost trade offs between a larger telescope operating less efficiently in a low orbit versus a smaller telescope operating efficiently in a geosynchronous orbit has not been performed. The issue of repairability must also be considered in this analysis.

Table 3 lists the spectroscopic capabilities the workshop participants thought desirable <u>and</u> practical for the Columbus mission. Of highest priority is the high resolution ($\lambda/\Delta\lambda \simeq 3 \times 10^4$) high throughput capability in the 912 to 1200 A region. Note that Space Telescope will have no capability below 1050 A and only an exceedingly restricted capability between 1060 and 1200 A. The other spectroscopic capabilities include medium resolution ($\lambda/\Delta\lambda \simeq 10^4$) spectroscopy between 1200 and 2000 A, and low resolution spectroscopy ($\lambda/\Delta\lambda \simeq 500$) for $\lambda < 900$ A and ($\lambda/\Delta\lambda \simeq 2000$) for $\lambda > 900$ A. The mode or modes operating below 900 A may extend the spectral coverage to 100 A.

The final complement of spectrographs can only be determined after a thorough study of the various packaging possibilities. For example, with clever design choices it may be possible to extend the high resolution ($\lambda/\Delta\lambda \simeq 3 \times 10^4$) capability well below 900 A. Some of the spectrograph designs being considered are rather new. For example see McClintock and Cash (1982), Cash (1982), Hettrick and Bowyer (1983), and Hettrick (1984).

For the discussions to follow on the science concerning the local ISM that could be accomplished with the Columbus mission, I will assume the wishes listed in Table 3 are indeed achieveable. In addition I will assume the spectrograph operating between 900 and 1200 A at a resolution of 3×10^4 also has the ability to record spectra of bright sources down to 600 A.

TABLE 3: COLUMBUS DESIGN SPECIFICATIONS

EUV and UV Capability	Far UV Capability*	UV Capability
λ = 100-2000 A	λ = 900-1200 A	λ = 1200-2000 A
$\lambda/\Delta\lambda = 500 \quad \lambda<900$	$\lambda/\Delta\lambda = 3\times10^4$	$\lambda/\Delta\lambda = 1\times10^4$
$\lambda/\Delta\lambda = 2000 \quad \lambda>900$		
Highest throughput posible.	For Exp = 10^5 sec want S/N = 30 on 18 mag blue object.	For Exp = 10^5 sec want S/N = 30 on 18 Mag blue object.
Imaging capability required.	Imaging capability desirable.	Imaging capability desirable.

*The far UV capability is the prime mission of Columbus.

SPECTROSCOPIC OVERVIEW OF SPACE TELESCOPE AND COLUMBUS SCIENCE

The spectral region extending from the atmospheric cutoff near 3100 A down to 100 A has been divided into three regions in the following discussions; region 1 from 1200 to 3200 A, region 2 from 912 to 1200 A and region 3 from 100 to 912 A. Space Telescope will mostly operate in region 1. The Columbus mission will likely emphasize observations in regions 2 and 3. All three of these regions contain resonance lines of many important interstellar species.

1. The Region 1200 to 3200 A

A partial listing of the many important lines in this region can be found in the various papers involving IUE studies of interstellar gas (e.g., Savage and de Boer 1982). More extensive lists are provided by Morton and Smith (1973). The latter list is relevant to Space Telescope planning because the HRS will likely be able to detect interstellar absorption lines about 200 times weaker than those that are routinely studied with IUE. In addition to the lines of such highly ionized species as N V, C IV, and Si IV, the region contains a multitude of lines of lower ionization. Of particular significance are the many lines of Si II, Fe II, and C I which permit an accessment of the degree of saturation of the absorption lines through curve of growth studies. Several of the very abundant atoms have low f value lines in this region. These include O I λ1355, C II λ2325, C III λ1909 and Si III λ1892. These transitions should produce lines on the linear part of the curve of growth and permit the derivation of accurate column densities.

A number of important molecules have their resonance transitions in the region 1200 to 3200 A. These include CO, C_2, H_2O, HCl, CH_2, OH, O_2, N_2, CS, and SiO. Although one does not normally associate molecules with the very nearby ISM, the detection of IR cirrus clouds (Low et al. 1984) and high latitude CO clouds (see Blitz, Magnani and Mundy, these proceedings) may force us to change our biased views.

2. The Region 912 to 1200 A

Table 4 lists the more important lines in the rich 912 to 1200 A region. Some of the most important transitions include:

a) The resonance lines of atomic H and D occur at 1025 A (Lyβ), 972 A (Lyγ), 950 A (Lyδ), with higher members extending to the Lyman continuum limit at 912 A.

b) The important electronic bands of molecular hydrogen (H_2) are the Lyman bands located at $\lambda < 1120$ A and the Werner bands at $\lambda < 1008$ A. The molecule HD has its band systems slightly displaced in wavelength from those of H_2.

c) The lines of O VI and S VI . These ions are formed at 3×10^5 K, a higher temperature than any interstellar ion observable in absorption with Space Telescope or IUE.

d) The lines of N I, II and III; P II, III, IV and V; S III, IV and VI; and Cl I, II, III and IV. The ability to probe multiple ionization stages is important for studying the thermal and nonthermal ionization processes in the local interstellar gas.

TABLE 4: SOME IMPORTANT LINES IN THE
912-1216 Å SPECTRAL RANGE

Species	Important Lines (Å)
H I, D I	1216, 1026, 973, 950, ..., 912
H_2, HD	hundreds of lines between 912 and 1120
C III	977, 1175
N I	951, 964, 1133, 1200
N II	916, 1084, 1085
N III	991
O VI	1032, 1038
A I	1048, 1066
P IV	951
P V	1118, 1128
S III	1012, 1190
S IV	1062
S VI	933, 944

3. The Region 100 to 912 A

Below 912 A the most important features are the lines of highly ionized plasma indicative of temperatures between 10^5 and 2×10^7 K. Figure 3 shows the wavelengths of many of these lines together with the temperatures corresponding to the maximum abundance of the various ions. Particularly noteworthy are the lines of Ne VII and VIII, Mg VIII, IX and X, and Fe IX, X, XII, XV, XVI, etc.

All of the strong resonance lines of He I and He II lie in this region. The He I lines (584, 537, 522 A...) lie in a series extending to the continuum edge at 504 A and the He II lines (304, 256, 243 A...) lie in another series extending to their edge at 228 A.

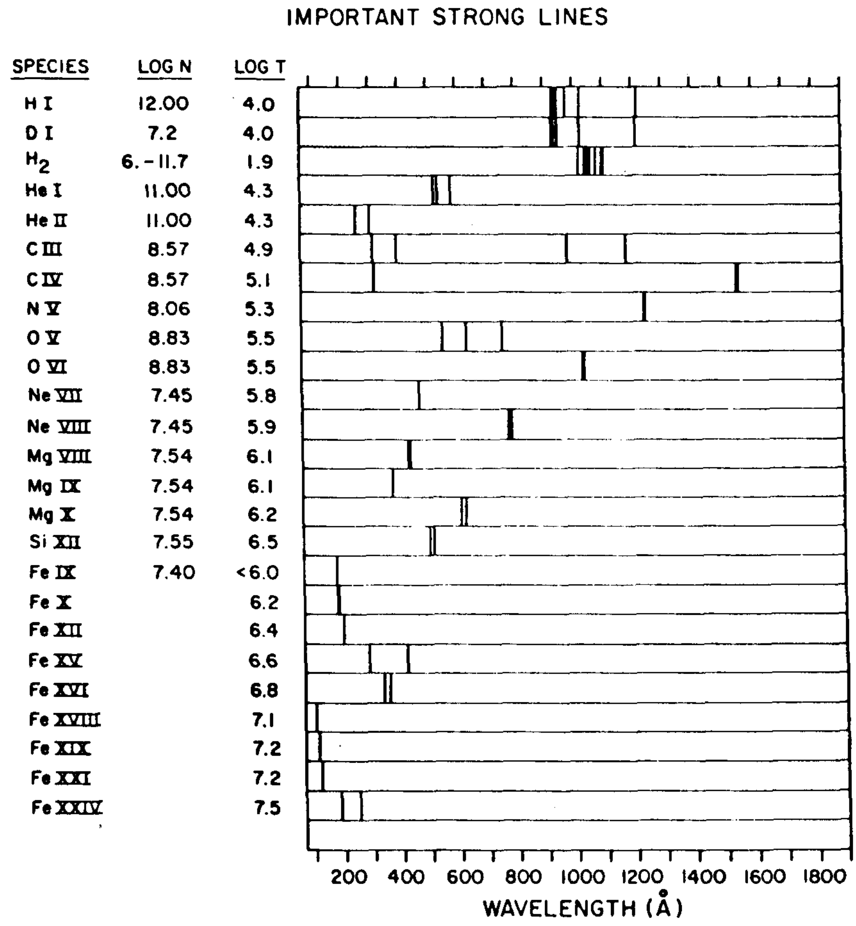

FIGURE 3
Wavelengths of important spectral lines of abundant elements and molecular hydrogen (H_2). Also indicated are the typical element abundances on a logarithmic scale where hydrogen is 12.00, and the temperatures of maximum fractional amount of each ion assuming collisional ionization equilibrium.

LOCAL ISM INVESTIGATIONS WITH THE ST HRS AND COLUMBUS INSTRUMENTS

The following section discusses a few of the many studies of the local ISM that might be undertaken with the ST HRS and Columbus spacecraft. No attempt has been made to indicate which instrument is the most appropriate for each investigation. Some brief comments can provide an overall summary; Columbus will be optimized for measurements of features with $\lambda < 1200$ A. The ST HRS will be most efficient for $\lambda > 1200$ A. However, the HRS will have very limited capability to 1060 A. The highest resolution mode of the HRS will have a resolution 2 to 3 times higher than that of Columbus.

1. Accurate Local Abundances

Both the HRS and Columbus will be able to provide resolutions and photometric accuracies significantly higher than previously available in the UV. These two important gains will lead to much more reliable estimates of absorption line column densities than now exist. For example, the 3 to 4 km s^{-1} resolution of the HRS combined with the ability to measure absorption lines less than 1% deep will almost certainly allow a reliable accessment of curve of growth problems. With accurate column densities and the ability to probe more than a 100 different ionic species a nearly unlimited range of scientific investigations is possible. Some examples include:

a) Depletion studies in local diffuse clouds and in the intercloud medium will provide new insights about the interplay between gas and dust.
b) Studies of the ionization structure of local gas using species having lines for a wide range of ion types, such as Si II, III, IV and S II, III, IV and VI.
c) Estimates of interstellar densities from the population of fine structure levels in such species as C II, Si II, Fe II, O I, N II, etc.
d) Direct temperature estimates for warm and hot gas from measures of thermal line widths.

2. Local Abundances of Cosmological Significance

Various light elements found in the ISM were likely created during the very early evolution of the universe. High precision measures of elemental abundances of these species in a variety of interstellar environments is of fundamental importance. The ST HRS and in particular Columbus will be able to accurately measure D/H in a number of local clouds through an analysis of the Lyman absorption lines. There is a small possibility that Columbus will have the resolution and sensitivity to also probe the He^3 to He^4 ratio from measures of the He I resonance line series starting at 584 A.

3. Local Gas Kinematics

The wavelength calibration of the HRS should allow absolute velocity measurements with an accuracy of about 0.5 km s^{-1}. With this velocity precision, it may be possible to investigate not only cloud motions but also the flow of matter into or out of clouds.

Accurate velocity measurements are important because the most powerful technique for confirming the spatial coexistence of two interstellar species is from a careful intercomparison of their absorption line profiles.

The large f value lines of the abundant ions of C II, Si III, N II, and C III can provide information on high velocity interstellar gas. With the high signal to noise data possible from the HRS and Columbus space craft, it should be possible to use these ions to search for very nearby but low column density, high velocity gas. Detecting this gas phase locally would provide important clues about shock heating in the local ISM.

4. The 3-Dimensional Structure of Local Gas

From studies with Copernicus and IUE we now have a better understanding of the 3 dimensional distribution of gas in the local ISM. Our knowledge of the local gas structure will continue to expand as instruments with greater sensitivity and resolution become available. The HRS will be able to more clearly separate interstellar Lyman α absorption from stellar Lyman α emission for nearby cool stars. Interstellar Lyman α will be accessible for very faint white dwarfs with the HRS at a resolution of 2000 in relatively short integration times. This ability to probe fainter targets relatively rapidly should eventually lead to a large increase in the number of local targets for which accurate H I column densities are available.

With Columbus the local H I distribution could be inferred from the Lyman lines or the Lyman discontinuity. However, a more exciting prospect is that of determining the local distribution of He I and He II from observations of hot white dwarfs at $\lambda < 600$ A.

5. Local Hot Gas

One of the most important species accessible between 912 and 1200 A is O VI. In collisional equilibrium the abundance of O VI peaks near 3×10^5 K. It is now thought that the O VI absorption seen by the Copernicus satellite is procuced at the boundaries of cooler clouds imbedded in a hot (10^6 K) medium. High S/N spectra of selected species including O VI over simple lines of sight will provide a test of the interface origin idea for O VI.

Copernicus studies of interstellar O VI were limited to O and B stars as the background targets. With Columbus, white dwarfs could be used to probe the local O VI distribution. If the white dwarfs provide a suitably smooth continuum it is possible that very broad O VI absorption associated with gas at 10^6 K could be detected.

The most exciting prospect for the direct detection of gas at 10^6 K or hotter from the Columbus mission will be provided with measurements at $\lambda < 912$ A. If the short wavelength spectrographs finally selected for Columbus have adequate resolution, then many of the species illustrated in Figure 3 may be detected over 100 pc paths. In the case of the lines of Fe this would yield data on ions spanning a temperature range from $\sim 10^6$ to $\sim 3 \times 10^7$ K. At this stage it appears doubtful that the Columbus spectrograph operating between 100 and 900 A will have adequate resolution. A more likely possibility is that the spectrograph designed to operate between 900 and 1200 A at a resolution of 3×10^4 will have coverage to shorter wavelengths with reduced but adequate resolution. If this instrument had spectroscopic coverage to 600 A, which seems reasonable, then the important Mg X and Ne VIII ions should be observable toward targets like HZ 43. Both these ions peak in abundance at temperatures near 10^6 K. The direct spectroscopic detection in absorption of local gas at 10^6 K would provide major insights about the nature of the local hot gas seen in emission at X-ray wavelengths.

6. Molecules in the Local ISM

Because of its great abundance and importance to interstellar chemistry, careful searches should be made for local interstellar H_2. In the H_2 survey of Savage et al. (1977), H_2 detections were reported for 8 stars with distances less than 100 pc. Studies of local H_2 with Columbus could yield new information on the local CO clouds recently discovered by Blitz, Magnani, and Mundy (1984).

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