Interstellar Medium

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Abstract. The study of the interstellar medium has been, and remains, a rich field for exploitation using small missions in the ultraviolet and X-ray spectral regions. I review the history of some such missions (of various sizes), and I also review the capabilities for study of the interstellar medium of "Hot Universe Background Explorer" (HUBE), as it was submitted in the second MIDEX round. A new technique for the three-dimensional visualization of the local interstellar medium is also exhibited.

INTRODUCTION

The emission line of Lyman α from cool stars has been available for use in study of the interstellar medium since the rocket measurement of Rottman, Moos, Barry, and Henry (1971). It is remarkable to contemplate the history of that measurement. Paul Patterson had completed a theoretical PhD thesis at Yale, under the direction of Ludwig Oster, examining the possibility of detection of the Lyman α emission line of cool stars by means of rocket observations. The issue was the concern that the stellar Lyman α emission might not be able to traverse interstellar space without being totally absorbed by the interstellar neutral hydrogen, which at that time was believed to have an average density of about 1 atom cm^{-3}. Patterson's rocket, intended to test the technique, was not a success, but Paul's idea stuck in my mind, and when Warren Moos asked me for a suggestion for a star to observe during the engineering gyro correction which was to occur at the beginning of a rocket flight to carry out UV spectroscopy of planets, I suggested Arcturus. We obtained a clear detection of Lyman α emission from Arcturus (following which the mission failed totally), and the chain from that observation, to the Johns Hopkins FUSE mission, is unbroken. Great oaks do indeed from little acorns grow! I have reviewed elsewhere (Henry et al. 1986) the succession of our subsequent observations of Lyman α emission from cool stars with, first, *Copernicus*, and then IUE: both of which were small (or medium-sized) space satellite missions. My interest quickly centered on the problem (which was pointed out to us by Don York) of determination of the cosmologically-important deuterium-to-hydrogen ratio. In Figure 1, I show our *most recent* results that have flowed out of that brilliant initial observation, our high-resolution HST observation of the emission line profile of (as one example) 31 Com (Dring et al. 1997). The deduced chromospheric emission line is shown as a thin line, which is cut in the middle by very strong absorption by the interstellar medium's neutral hydrogen and deuterium. The absorption, while strong, is of course not as strong as had been initially feared.

The interstellar deuterium which we observe must be of primordial origin, perhaps replenished by inflame from high-velocity clouds. Linsky et al. (1996) have especially emphasized the importance of these deuterium observations for study of the interstellar medium, since the data analysis is so much more certain for the deuterium than it is for the highly-saturated hydrogen line.

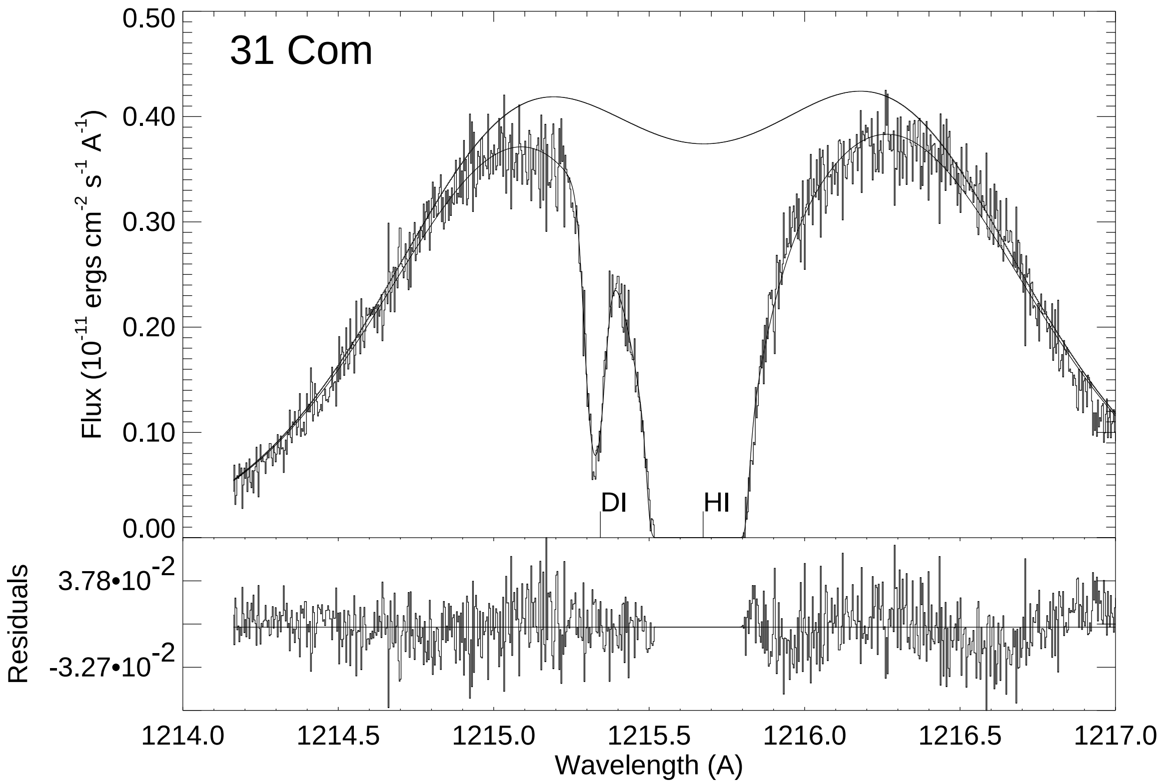

Fig. 1.— Interstellar absorption of hydrogen and deuterium Lyman α, seen against the chromospheric Lyman a emission line of the cool star 31 Com. While the deuterium-to-hydrogen ratio is of great interest for cosmology, it is also of great interest for study of the destruction of deuterium in stars as the galaxy evolves. The column density of hydrogen is, of course, also itself of great interest, for study of the interstellar medium; and deuterium observations of the column density are more secure than are hydrogen observations, because the deuterium line is so much weaker than is that of hydrogen itself. Our measurements of the column density of hydrogen, in the direction of many stars, form the raw material for the construction of three-dimensional maps of the structure of the local interstellar medium, as appears in Figure 3.

Thus we have seen an almost perfect example of the role of small missions, which fill in from the initial discovery, via sounding rockets, to the fully-mature observations using, in this case, the Hubble Space Telescope. One result of this chain of missions, is new understanding of the interstellar medium. In particular, once a sufficient number of lines of sight have been examined to determine column density, a three-dimensional map of the local interstellar medium can be constructed.

I introduce here a new technique for visualizing the results of such study of the interstellar medium, the use of "crossed-eye" stereoscopic images. In Figure 2, so as to allow the reader to practice the technique with a simple but vivid example, I show "snowflakes" that I have created. All that is necessary is that the reader cross his or her eyes, and superimpose the two images. A very clear three-dimensional image should jump out. Russ (1995) tells us "in many of the images [in this chapter], two adjacent images in a rotation or pseudo-rotation sequence can be viewed as a stereo pair. For some readers looking at them will require an inexpensive viewer which allows one to focus on the separate images while keeping the eyes looking straight ahead (which the brain expects to correspond to objects at a great distance). Other readers may have mastered the trick of fusing such printed stereo views without assistance. Some, unfortunately, will not be able to see them at all. A significant portion of the population seems not to actually use stereo vision, due for instance to uncorrected amblyopia ("lazy eye") in childhood." What Russ fails to point out is that the images that are needed for viewing with a viewer are not the same as the images that are needed for viewing with eyes crossed. You may see the difference at http://msx4.pha.jhu.edu/khuuleDir/stereo.html, where you will find a color version of Figure 2, plus the same figure done so as to be viewable correctly with a stereo viewer. The difference in the images becomes quite clear, when you view the latter with the crossed-eye technique.

In Figure 3, I use this new technique to provide a three-dimensional preview of the local interstellar medium. I call it a preview, because the data set on which it is based have not yet been published (Linsky et al. 1996), and so the representation must be regarded as provisional

Fig.2.—Three-dimensional image: cross your eyes, and superimpose the two images. A vivid three dimensional image of snowflakes should materialize. This figure is an "engineering test;" the technique is applied to visualization of the local interstellar medium in Figure 3. The two images need to be reversed if one wishes to use a stereoscopic viewer in place of the crossed-eye technique.

only. Nevertheless, the figure clearly indicates the potential of the technique for three-dimensional visualization. The Sun is located in the Local Interstellar Cloud (LIC), which has two components with slightly different motions. This cloud is partially ionized and is at a temperature of about 7000K. The local cloud is surrounded by a highly ionized bubble, which extends to more than 100 pc, depending on direction.

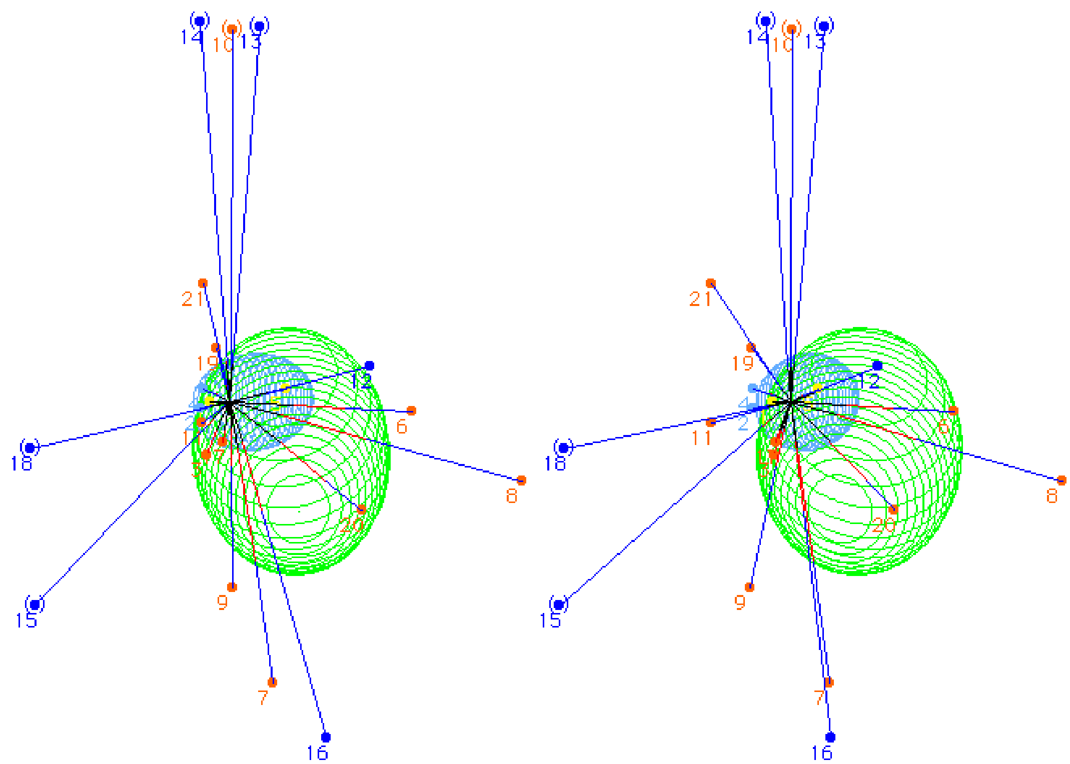

Fig. 3.—Three-dimensional image: a provisional image of the local interstellar medium. Numbered lines-of-sight to various stars are shown (for example, 31 Com is #10). The North Galactic Pole is at the top of the figure, and the Galactic Center lies to the left. Two overlapping local clouds of interstellar gas are seen. The properties of the clouds have been deduced by Linsky, Piskunov, and Wood (1996) from the observed column densities on the various lines of sight that are shown.

FUTURE MISSIONS

Let me highlight, as an example of possible future missions, "*Hot Universe Background Explorer,*" HUBE, as it was submitted to the second NASA MIDEX round. In that submission, thanks to the kind cooperation of Wilt Sanders and his colleagues, I was joined by John M. Harlander, Jeffrey J. Bloch, and Barham W. Smith, with whose crucial aid I was able to include HUBE-ISHS (Imaging Spatial Heterodyne Spectrometer) as part of the HUBE payload. The capabilities of HUBE-ISHS for high-resolution spectroscopy of C IV emission from the interstellar medium are shown in Figure 4.

The MIDEX platform is of sufficient capacity that the HUBE proposed mission could

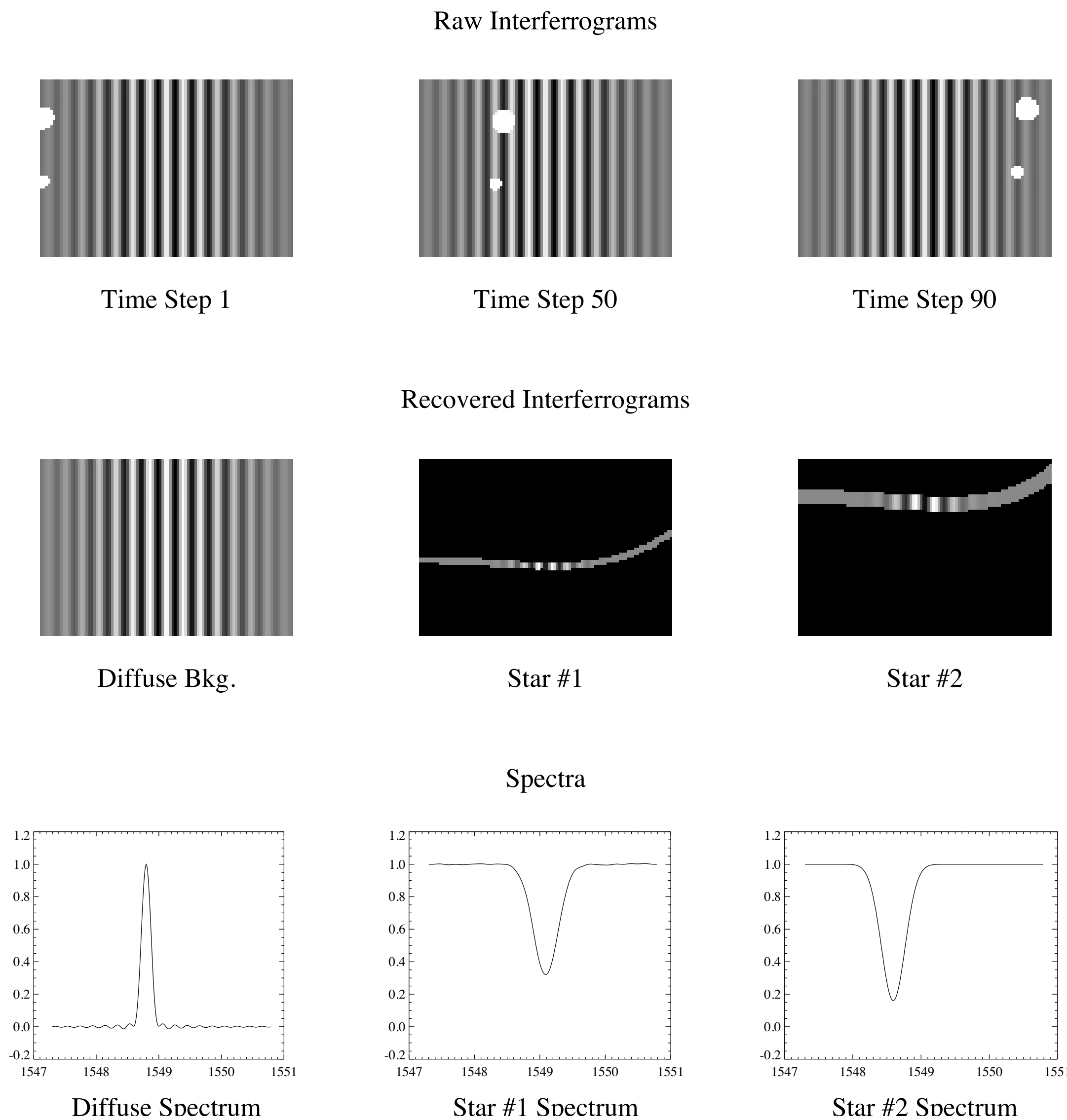

Fig. 4.— HUBE-ISHS carries out high-resolution spectroscopy of the diffuse C IV radiation in the galaxy. With no de-convolution required, there is clean separation of the emission spectra of point sources and the diffuse background. This figure was created by John M. Harlander. The instrumental technique is described by Harlander (1991), Harlander and Roessler (1990), and Harlander, Roessler,

Reynolds, Jaehnig, and Sanders (1993). The spectral resolution of HUBE-ISHS is 15 km s^{-1} which is better than IUE high resolution, and comparable to HST-GHRS.

also include X-ray spectroscopy of the interstellar medium. To achieve this, I was joined by David N. Burrows, the Principal Investigator for CUBIC (Burrows 1996). Figure 5 gives the reader some idea of the remarkable capability of CUBIC for providing high-resolution spectroscopy of the interstellar medium. I have presented the other ultraviolet spectroscopic capabilities (Table 1) of HUBE elsewhere (Henry 1999a). Also, the synergism of the HUBE ultraviolet spectroscopy with ISHS and CUBIC for analysis of the Cygnus Loop nebula, as an example, has been comprehensively illustrated in Henry (1999b).

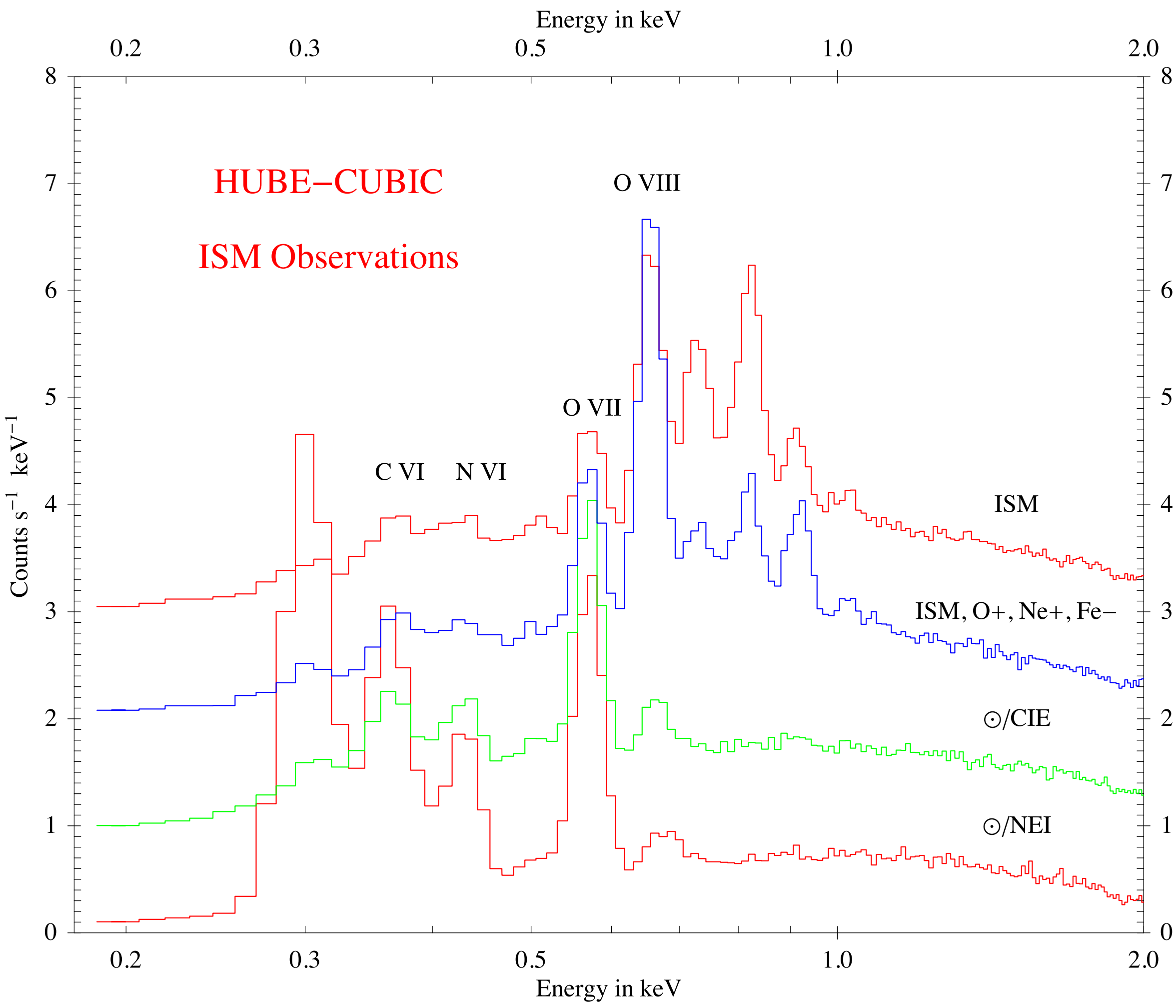

Fig. 5.— HUBE-CUBIC carries out high-resolution X-ray spectroscopy of the diffuse radiation of the galaxy. I have created this figure from simulations that were provided by David N. Burrows. The top curve shows CUBIC response to a standard two-component model of the ISM, based on proportional counter fits to the high latitude diffuse X-Ray background (Nousek 1978). The second curve is identical except that the abundances of O and Ne have been increased by 50% while that of Fe has been reduced by half, resulting in large changes in the relevant lines. The third spectrum is for a single temperature, solar abundance, collisional ionization equilibrium (CIE) model fitted to CCD sounding rocket data for a similar high latitude direction, while the bottom spectrum is for the same model, but in nonequilibrium ionization (NEI) with an ionization parameter of log(nt) = 10.0. CUBIC will be able to measure abundances to 25% accuracy and will readily distinguish between CIE and NEI conditions, as well as between single and multiple-temperature plasmas.

Table 1. Instruments that were proposed for the second MIDEX submission of HUBE

Instrument	λλ (Å)	Prime Science Goal
EUVS (Extreme-Ultraviolet Spectrometer)	850 – 1200	Map O VI; high-latitude UV bkgd
LαS (Lyman α Straddle Spectrometer)	850 – 1400	Detect UV bkgd step at 1216 Å
SHS (Spatial Heterodyne Spectrometer)	1530 –1570	*Velocity-resolved* CIV maps
CUBIC (X-ray spectrometer)	1.2 – 250	Origin of the Cosmic X-ray bkgd
FUVS (Far-Ultraviolet Spectrometer)	1230 – 1800	UV bkgd continuum; C IV, N V, …
UVI (Ultraviolet imager)	1350 – 1600	2-λ map of the diffuse background

CUBIC is an ideal choice for the first all-sky high-spectral-resolution X-ray spectroscopic survey, because of its high spectral resolution, its simplicity, and its robustness. CUBIC is

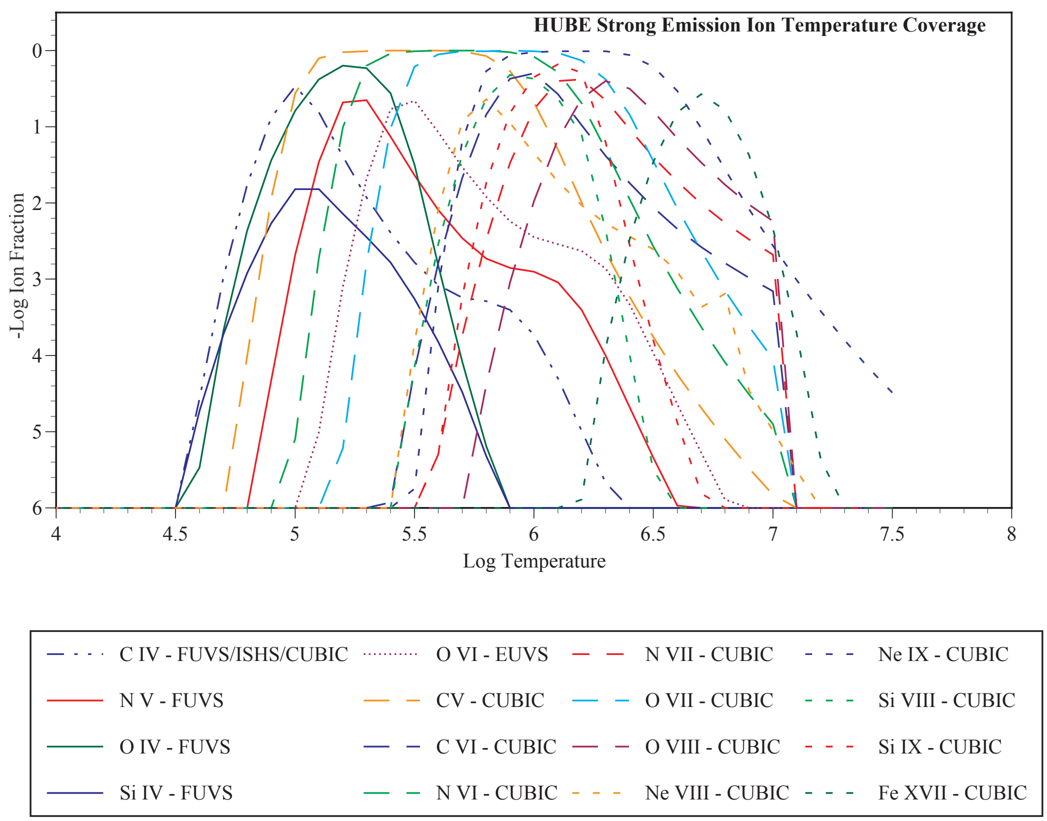

Fig. 6.— HUBE, as proposed in the second MIDEX round, carried a range of instruments that have the spectroscopic capabilities that are summarized in this figure by Jeffrey J. Bloch. HUBE-ISHS and HUBE-CUBIC have been described to some extent in the present paper. HUBE-EUVS and HUBE-FUVS are described by Henry (1999a). The capabilities of all of these instruments together to provide comprehensive analysis of the Cygnus Loop nebula (as an example) is described by Henry (1999b). As you can see from the present figure, little of the interstellar medium could escape HUBE's spectroscopic scrutiny.

significantly more sensitive than any previous X-ray mission except HEAO-1, and CUBIC provides an 8-fold increase in spectral resolution over HEAO-1.

While it *is* possible to achieve *still* higher spectral resolution by use of a cryogenically-cooled detector, such a mission has limited lifetime and would be much more effective as a follow-up mission to CUBIC, to resolve any regions that remain spectroscopically-confused. Such regions should be few; see Figure 5.

The exceptional completeness of HUBE as a mission for spectroscopic analysis of the interstellar medium is demonstrated in Figure 6, which shows the ion temperature coverage of the complement of instruments (Table 1) that made up HUBE in its second MIDEX incarnation. Particularly important is the fact that several ionization stages of important elements are included, and that ions (such as O VI) are observed in emission, that are also observed in absorption by other planned missions (in the case of O VI, the FUSE mission).

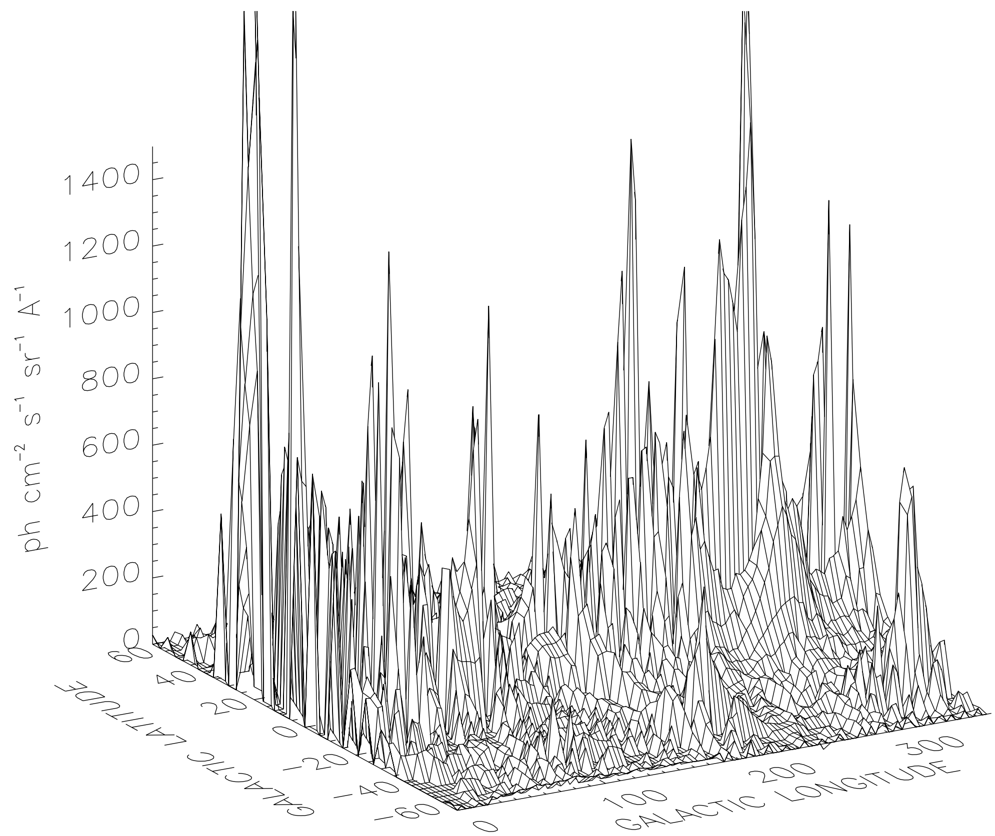

Fig. 7.— Model (Murthy and Henry 1995) of the expected distribution of ultraviolet light that has been scattered once from interstellar dust. The dust is assumed to be very strongly forward-scattering in this model, which explains the patchy appearance: individual stars can create patches of forward-scattered light. Attempts to determine the albedo and scattering parameter of the dust grains are clearly doomed to failure, if they rely on a few scans as a function of galactic latitude. A detailed map of the sky in the ultraviolet, however, could unambiguously determine the albedo and scattering parameter.

INTERSTELLAR DUST

My final topic is interstellar dust, and the profound role it plays, not only in astrophysical processes, but in hindering our observation of the interstellar medium. Two views of strongly-forward-scattering interstellar dust as viewed from our location in the galaxy are given in Figures 7 and 8. The two figures are different representations of the same data, namely one of the models of dust-scattered starlight of Murthy and Henry (1995). The particular model that I have chosen for display is one I believe to be close to the truth: one in which the Henyey-Greenstein scattering parameter $g = 0.9$, corresponding to very strong forward scattering.
Note that if this model provides an accurate representation of what really occurs, the pattern of scattered starlight over the sky is very asymmetric. This partly reflects the asymmetric pattern of the ultimate, underlying, source of the radiation, the UV-emitting stars, which are located mainly in Gould's belt; but also reflects the very strong absorption of light from more distant stars (which are distributed much more symmetrically with respect to galactic coordinates.) The region in the Galactic Plane that is dimmest in Figure 8 is also nearly devoid of direct UV light from stars, as may be seen in Murthy and Henry (1995): they show a model, plus an integration of the starlight that was actually observed in the TD-1 mission.

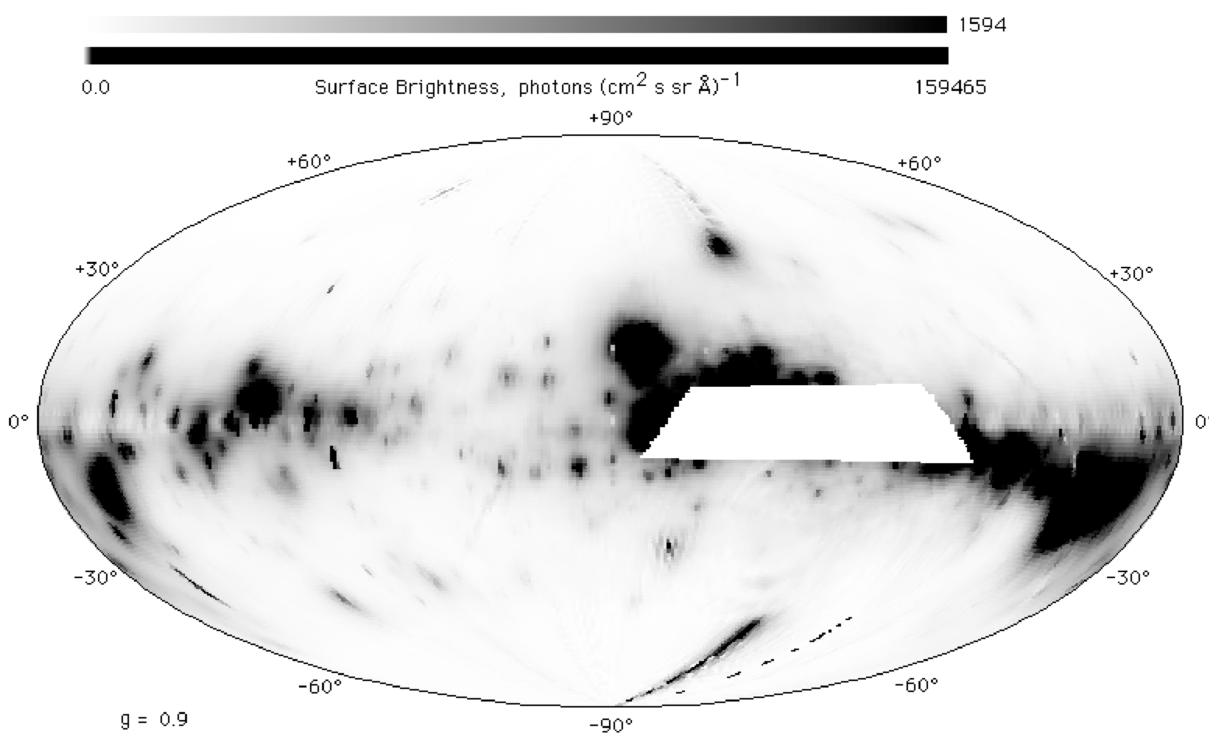

Fig. 8.— Model of the expected distribution of ultraviolet light that has been singly-scattered from interstellar dust. This is a different presentation of the same model that is shown in Figure 7. In the present representation, the North Galactic Pole is at the top of the figure, and the Galactic Center is at the center of the figure. Galactic longitude increases to the left, as you look at the figure. Gould's belt is tipped 19° with respect to the Galactic Plane. A region where no H I data were available is left blank. The model is graced with a few artifacts.

The correct values of for albedo and for the Henyey-Greenstein scattering parameter in the ultraviolet are not well established yet. The situation has been reviewed by Bowyer (1991); see also Witt et al. (1992), Witt and Petersohn (1994), and Henry and Murthy (1993). It is clear from Figures 7 and 8 that what is needed to resolve all issues, is an all-sky map of the distribution of the scattered starlight in the ultraviolet. It should be entirely possible to unambiguously assign values to the albedo and scattering parameters from such a map, assuming, of course, that these parameters have a unique value, which is not likely to be the case. Regardless of the latter concern, an all-sky map of the UV scattered light is clearly a high priority.

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