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S. Bowyer *

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Center for EUV Astrophysics
2150 Kittredge Street
University of California
Berkeley, CA 94720

Preliminary Science Results from the Extreme Ultraviolet Explorer

Stuart Bowyer
Center for EUV Astrophysics, 2150 Kittredge Street, University of California, Berkeley, CA 94720

Abstract. The Extreme Ultraviolet Explorer has completed the first all-sky all-band survey for extreme ultraviolet (EUV) sources. Four all-sky maps have been obtained, centered at 100 Å, 200 Å, 400 Å, and 600 Å. A preliminary report on these results will be presented. The guest observer (GO) phase of the mission using the Deep Survey/Spectrometer telescope has begun, and a wide range of astrophysical topics are now being investigated. Highlights of the results obtained to date will be presented.

Key words: EUVE satellite, galactic astronomy

1 Introduction

The Extreme Ultraviolet Explorer (EUVE) satellite has just completed its first year of successful on-orbit observations after being launched on 7 June, 1992, from Kennedy Space Center by a Delta II rocket. The science instrument payload was designed and built at the Center for EUV Astrophysics and Space Sciences Laboratory at the University of California, Berkeley, and consists of three grazing incidence scanning telescopes, three extreme ultraviolet (EUV) spectrometers, and a deep survey/spectrometer telescope [1]. After a one month on-orbit check-out phase, EUVE then completed a six month all-sky survey in four EUV photometric bandpasses (50–180 Å, 160–240 Å, 345–605 Å, and 500–740 Å). Concurrent with this sky survey was the operation of a short wavelength (65–190 Å and 160–360 Å) deep survey in a 2° wide swath along half of the ecliptic at a sensitivity some 10 to 50 times that of the all-sky survey. On 22 January, 1993, guest observer (GO) spectroscopic observations began using three spectral channels covering the 70–760 Å region at a spectral resolving power of ≈ 250.

At this time of writing, all the instruments exceed or meet each operational requirement, and the mission has now operated for over 14 months with no major interruptions or instrument failures. A detailed review of the on-orbit performance of these instruments can be found in the EUV GO Handbook [19].

In this review article we discuss some of the highlights from the first year of the operation of EUVE. This includes some preliminary science results from the all-sky survey and a few selected highlights from the first EUV spectroscopic observations. The major conclusion from these early stages of the mission is that, contrary to some pessimistic prelaunch predictions, the EUV sky is rich in a wide variety of astrophysical sources whose observation will result in some fundamentally new scientific discoveries. Of particular note is the recent publication of the EUVE Bright Source List [15] which contains some 350 of the brightest sources detected in the all-sky survey. Although further data analysis is still proceeding on these

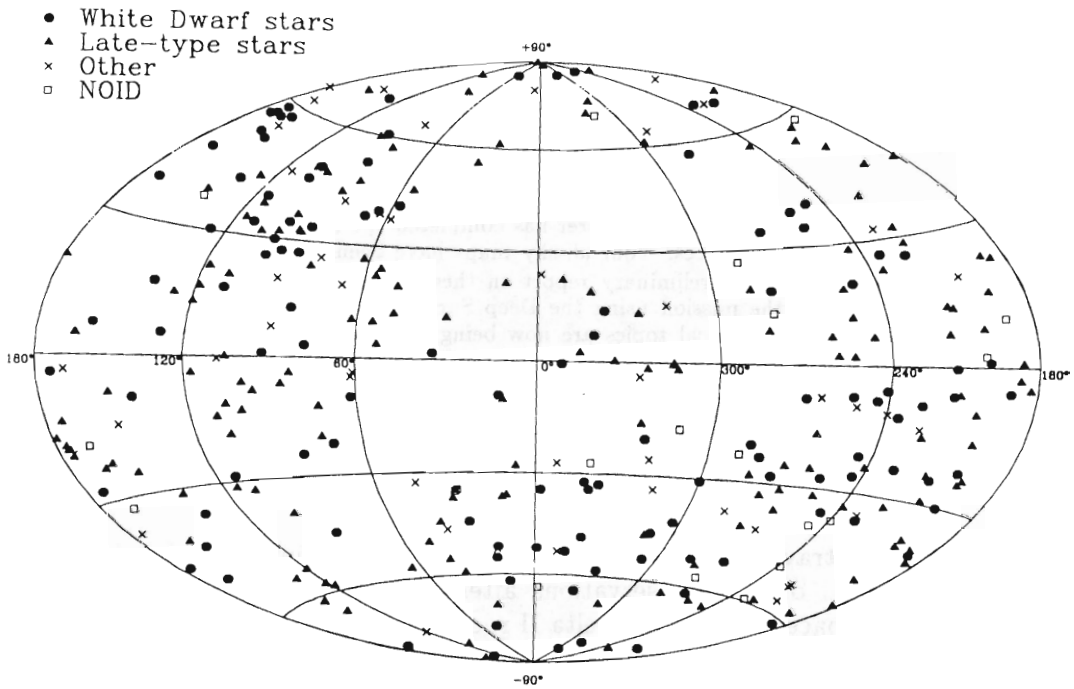

Fig. 1. The distribution of the 356 sources for the Bright Source List in galactic coordinates.

data, preliminary estimates indicate that between 1000 and 3000 EUV sources will eventually be cataloged by EUVE. This is in stark contrast to the dozen or so EUV sources known of a decade ago.

2 All-Sky Survey and Spectroscopic Highlights

Preliminary results for this four band survey are listed in the EUVE Bright Source List [15]. Those sources with reliable optical identifications fall into the following categories: 55% late-type stars, 30% hot white dwarfs, 4% cataclysmic variable stars, 3% active galactic nuclei, 4% early-type stars, 1% nuclei of planetary nebulae, and 2% other types of sources (e.g., Hercules X-1). Approximately 6% of the brightest sources have no currently assigned optical identification. The all-sky distribution of these sources is plotted on the galactic Aitoff projection of Figure 1.

2.1 B Stars

A major surprise in the sky-survey data was the discovery of the brightest EUV source, ϵ CMa [22]. This B2II star was strongly detected in the two long wavelength EUVE bandpasses with a flux in the longest wavelength band (500–740 Å) some 30

times that of the previously believed brightest source, the hot white dwarf HZ 43. Several predictions had been made before launch concerning the detectability of main sequence B stars in the EUV [4, 12], indicating that both short wavelength emission caused by shock-heated stellar winds and strong long wavelength emission from the B star photosphere would be observed. Although the intrinsic level of EUV emission from B stars was predicted to be appreciable, the great intensity observed towards ϵ CMa is mainly due to its location in a region of very low interstellar hydrogen column density ($N(\mathrm{H}) \approx 1.0 \times 10^{18}$ cm^{-2}). This region is, in fact, an interstellar tunnel some 50 pc in diameter and 300 pc long, which appears to be virtually free of neutral gas, and is thought to be an extension of the Local Bubble in the general direction of the (also EUV bright) B star, β CMa.

Follow-up EUVE spectroscopic observations of ϵ CMa by Cassinelli et al. (1993) have shown it to be extremely rich in stellar photospheric emission lines longward of $\approx$ 450 Å, and to possess short wavelength lines at $\approx$ 170 Å probably due to emission from shock-heated stellar winds. Preliminary fits to the photospheric spectrum using standard B star model atmospheres have failed to reproduce both the numbers and type of observed spectral features and the level of emission by a factor of $\approx$ 30. This apparent underestimation of the photospheric EUV flux from nearby B stars may well prove problematic with regard to previous estimates of the photoionization sources of the local interstellar gas [3].

2.2 Extragalactic Sources

During the on-orbit checkout phase of the mission, serendipitous observations of the BL Lac object PKS 2155–304 revealed it to be a detectable source of extragalactic EUV emission longward of 100 Å. EUV light curves show about a 10% variation in output over a 1.3 day observing period, in sharp contrast to the more extreme variability of this object at both hard X-ray and ultraviolet wavelengths [16]. Follow-up spectroscopic observations of this active galactic nucleus (AGN; shown in Figure 2) indicate that there is continuum emission out to $\approx$ 120 Å, which is currently being modeled using various synchrotron emission mechanisms [10].

The all-sky survey detected a total of six extragalactic objects in the 50–180 Å range consisting of two AGN (Mk 279 and 1H0419–577) and four BL Lac objects (Mk 421, Mk 180, Mk 501, and PKS 2155–304). The detection of extragalactic sources of EUV radiation indicates that there must be several low column density lines of sight that extend right into the the galactic halo. Thus, it would appear that the low density Local Bubble region may well not be bounded at high galactic latitudes.

2.3 Hot White Dwarfs

Ever since the first detection of an EUV source (the hot white dwarf star, HZ 43) on the Apollo-Soyuz mission by Lampton et al. (1976), large numbers of white dwarfs were expected to appear in the EUVE all-sky survey. However, only about

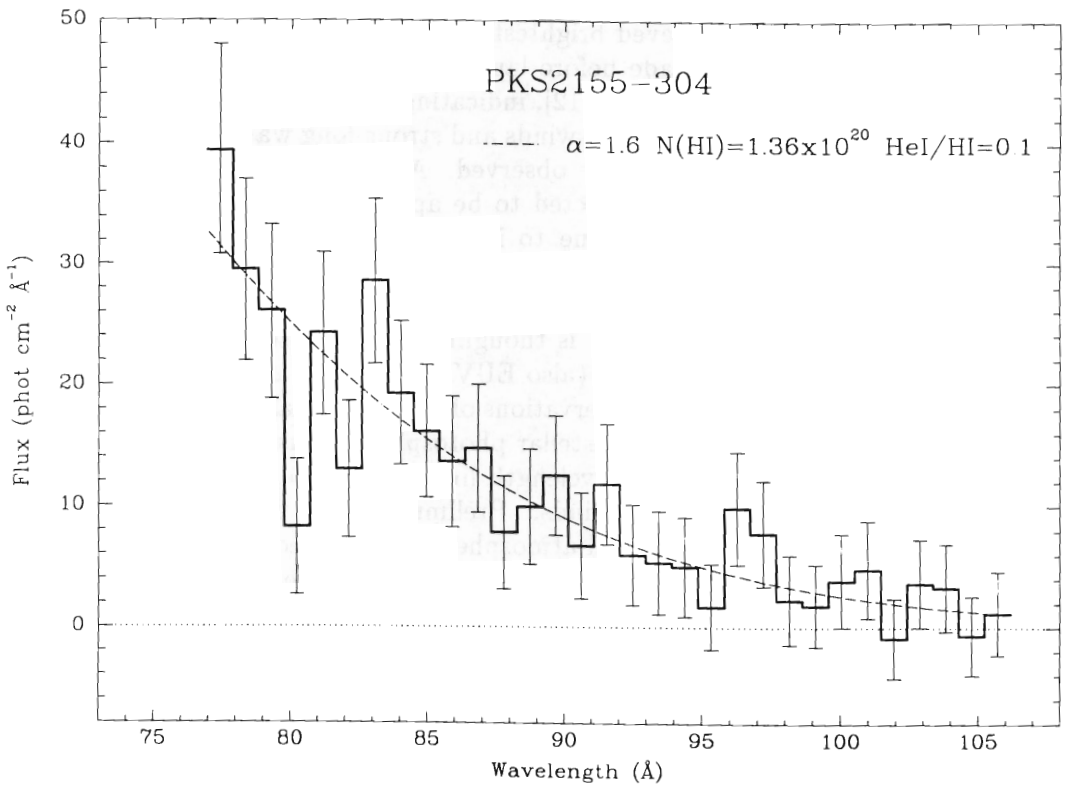

Fig. 2. Background-subtracted EUVE spectrum of PKS 2155−304 deconvolved by the effective area of the short wavelength spectrometer. The best-fit power law + absorption with energy index of 1.6, neutral hydrogen column density N(H I) = 1.36×10^{20} cm^{-2} and neutral helium column density N(He I) = 1.36×10^{19} cm^{-2} is shown as a dashed line.

one-third of the sources listed in the Bright Source List are white dwarfs, compared with almost twice this number of late-type stars. In Figure 3 we show the galactic distribution of white dwarfs [21], and it is immediately apparent that their spatial distribution is far from uniform. Since white dwarfs are apparently being detected at distances much greater than the late-type stars, we conclude that they must be subject to interstellar absorption beyond the region in which most of the late-type stars have been detected. Note the apparent lack of white dwarfs in the region above the galactic center for longitudes between 300° − 60° and latitudes > 20°, which coincides with a known local absorbing cloud with a distance of ≈ 80 pc. EUV spectral studies of white dwarfs have proven doubly interesting. First, the EUV data can be used to constrain the physical parameters needed to model their atmospheres. Second, the EUV continuum can be used as a background source to measure the effects of interstellar hydrogen and helium absorption along the line of sight. For example, the medium wavelength spectrum of the hot white dwarf GD246 shown in Figure 4 clearly exhibits features that necessitate EUV

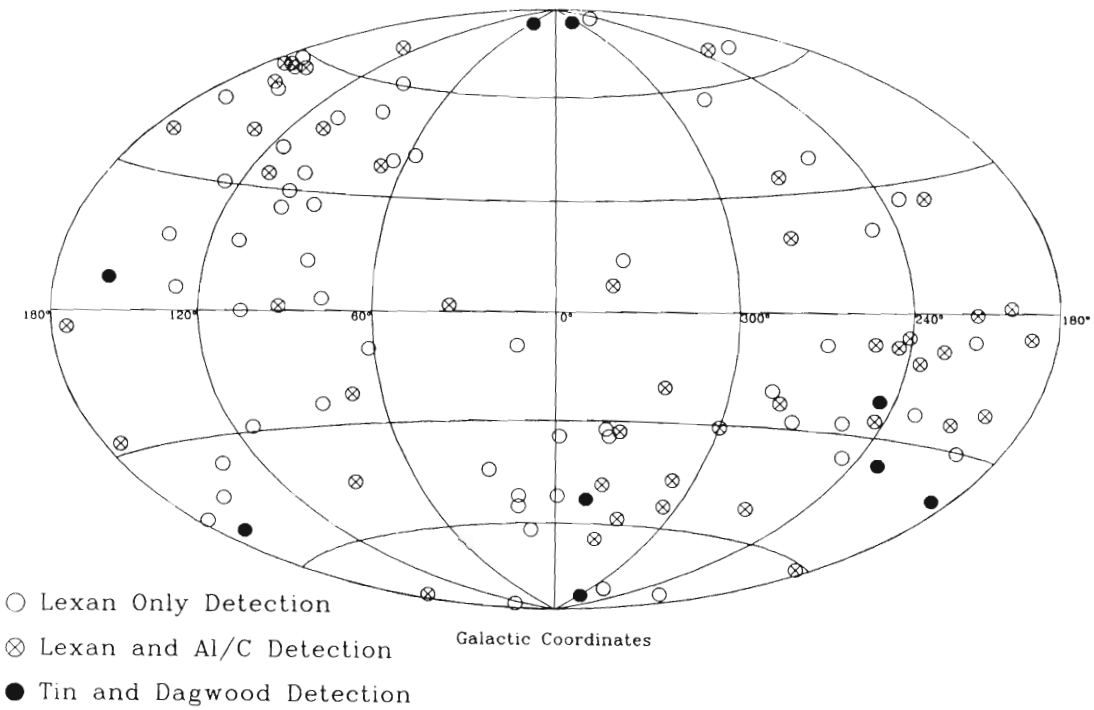

Fig. 3. The sky distribution of white dwarfs as detected by the EUVE all-sky survey.

emission from an atmosphere that radically departs from a pure hydrogen model, as initially predicted by Vennes (1992). The long wavelength spectrum of the DA white dwarf G191–B2B has been used by Dupuis et al. (1993) to derive a neutral interstellar hydrogen to helium ratio of ≈ 14 along the 50 pc to this source, favoring higher ionization of helium in the local interstellar medium if they assume a normal cosmic abundance ratio of 10. There are many more sources for which this method of interstellar column density and element abundance measurement can be applied, thus providing an important source of information on the structure of the local gas.

2.4 Late-Type Stars

It is clear from the large numbers of late-type stars detected by the EUVE sky survey that these data will have a large impact on our current understanding of the physics of coronal emission. The nearby late-type dwarfs, α Cen (G2V + K1V) and HR 6094 (G5V), have been observed by Vedder et al. (1993). An emission measure analysis of the α Cen four-band EUVE photometry data indicates two distinct temperature components for the a Cen binary system; one with a temperature of 8.5×10^5 K (which matches three of the EUV fluxes and the previous X-ray observations), and a second component with a temperature of 1.0×10^5 K

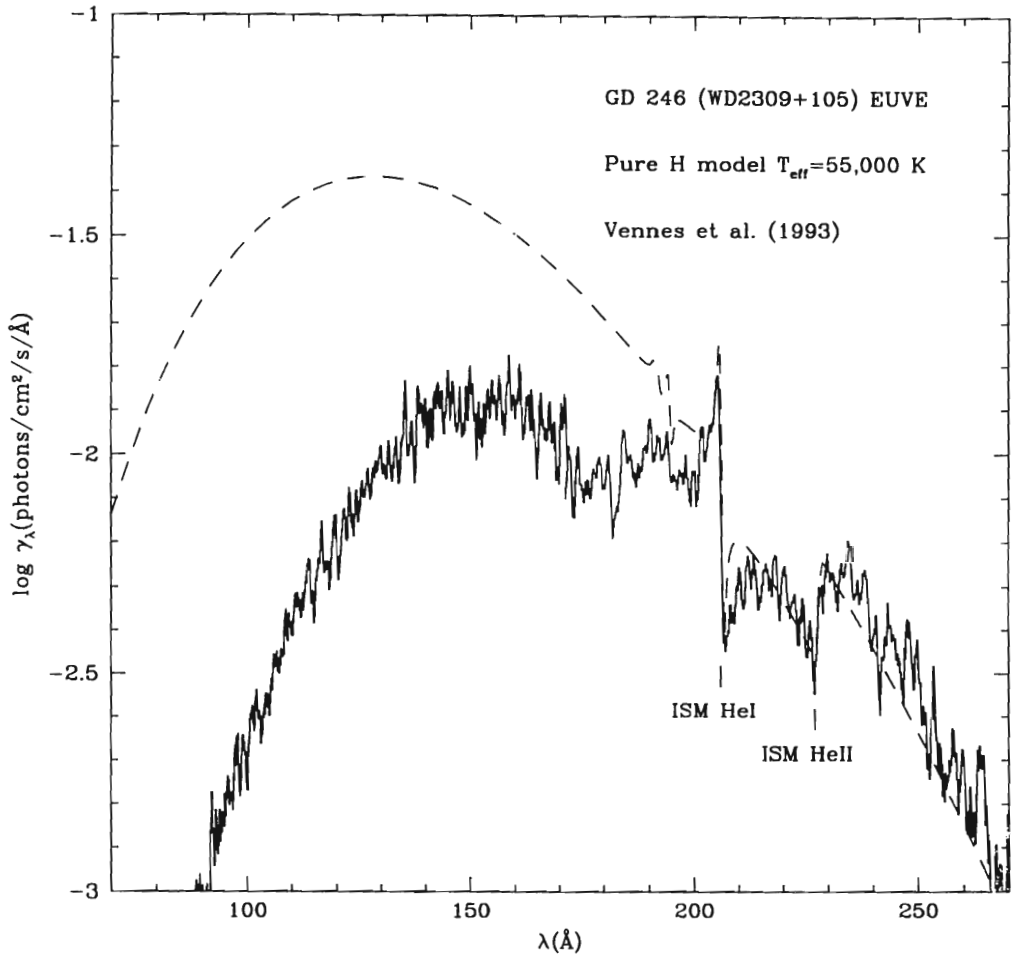

Fig. 4. Extreme ultraviolet spectrum of the hot hydrogen-rich white dwarf GD 246. Two outstanding features at 206 Å and 228 Å are attributed to absorption in the interstellar medium. EUV emission in these objects was, in the past, assumed to be dominated by hydrogen; but clearly, additional sources of opacity are observed at $\lambda < 200$ Å.

consistent with the fourth EUV photometric measurement and the International Ultraviolet Explorer (IUE) CIV results. The observed EUVE count rates severely constrain the amount of material in the outer atmosphere to between 10^5 K and 10^6 K, implying a steeper differential emission measure distribution than previously thought.

EUV spectroscopy of the G0III binary system of Capella by Dupree et al. (1993) shows a rich emission spectrum across the entire 70–760 Å region which is dominated by high ionization iron emission lines. A continuous distribution of temperatures (10^5 K to $10^{7.8}$ K) is present in the Capella system, and in particular there appears to be a minimum in the emission measure distribution at

$\approx$ 1 million K. This differs from the solar atmosphere whose minimum occurs at $\approx$ 160,000 K, the temperature at which the maximum radiative loss rate for a collisionally ionized plasma occurs. Hence, the EUVE data for Capella suggest a different atmospheric temperature structure possibly caused by a fast wind.

2.5 Planetary Studies

EUVE has already made observations of three solar system objects, the Moon, Mars and the Jupiter-Io system. During the all-sky survey the Moon was observed on several occasions, and Gladstone et al. (1993) have reported surface albedo measurements over the entire 70–760 Å range, which can be modeled using the scaled reflectivities of SiO_2 and Al_2O_3. Striking EUV images of the Moon at first quarter stage are shown in Figure 5, and such data are being used by McDonald and Gladstone (1993) to monitor the variation of solar EUV flux as reflected by the lunar surface.

Similarly exciting EUV images of the Io torus around Jupiter have been obtained by Moos et al. (1993). Although scientists have known about this hot, gaseous toroidal feature since it was first pictured in the EUV by Voyager in 1979, it had never been imaged in its entirity until the recent EUVE observations. Since it is known that the Io torus changes rapidly, the present snapshot images taken by EUVE will provide a very sensitive probe into the temperature variations along the entire torus. Such information is relevant to the explanation of how the energy and material are supplied to the torus and how this interacts with the far larger Jovian magnetosphere.

EUV spectral observations of the Martian atmosphere by Chakrabarti et al. (1993) have revealed the first detection of helium on Mars through observation of the 584 Å emission line. These measurements have been used to derive the He mixing ratio, which can be combined with existing Martian data to estimate the radiogenic heat flux of the planet; this is directly related to the original material in the Martian protoplanetary cloud.

2.6 Local Interstellar Medium Studies

It had long been assumed that all sources of interstellar opacity had been fully identified prior to the launch of EUVE (e.g., Cruddace 1974). However, Rumph, Bowyer and Vennes (1993) have reported the remarkable discovery of the autoionization resonance features of neutral helium in the continuum spectra of several hot white dwarfs at a rest wavelength of 206 Å. The discovery and detection of this absorption edge has allowed the direct measurement of the interstellar column density of neutral helium along these lines of sight, which, when combined with similar observations of the HeII edge at 228 Å, is providing a new technique for determining the ionization state of the local interstellar gas.

It is clear that these EUVE observations are providing a unique tool in determining both the spatial extent and physical properties of the Sun's near neighborhood. A recent discovery concerning the Local Bubble morphology has been

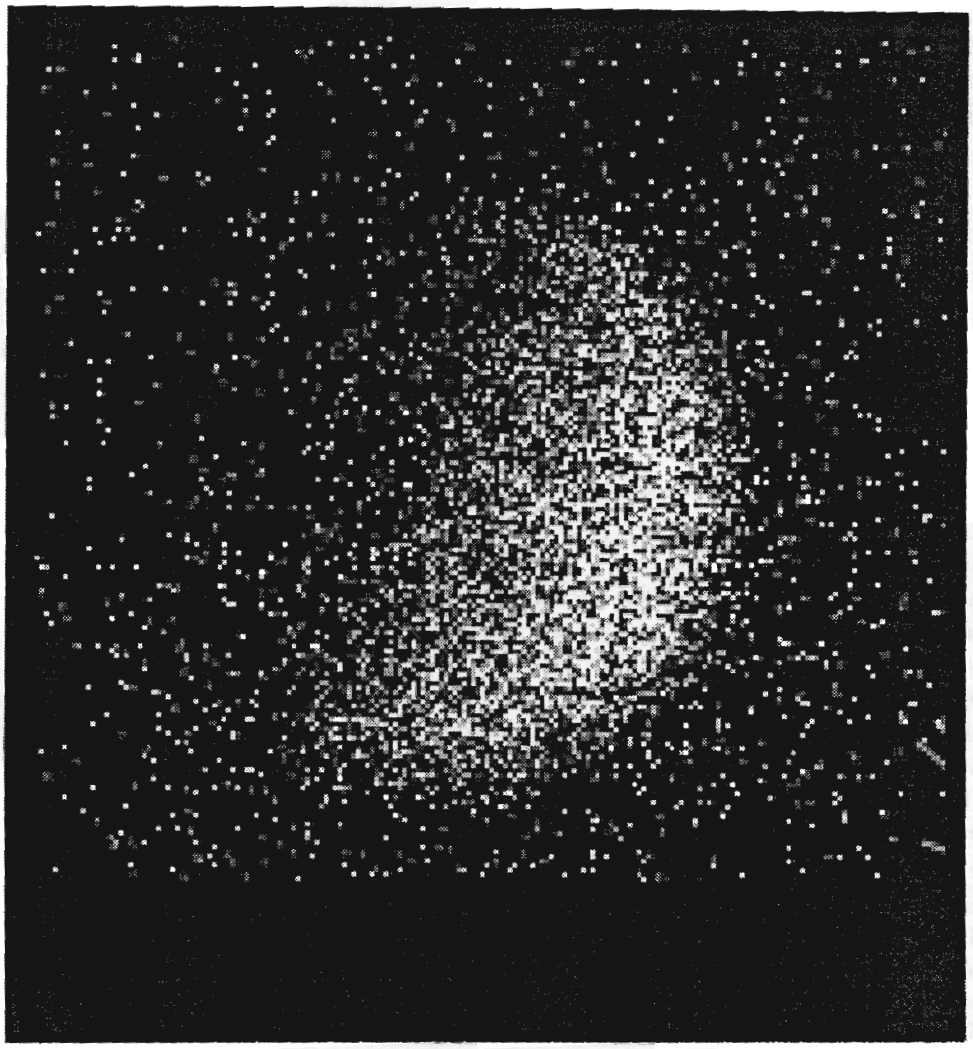

Fig. 5. Last quarter Moon across whole wavelength range of EUVE

the detection of a shadow in the diffuse EUV background by Lieu et al. (1993). Prolonged observations of the diffuse background along the ecliptic plane using the Deep Survey telescope have revealed this emission to be spatially anti-correlated with Infrared Astronomical Satellite (IRAS) 100 μm flux from cloud features, with one statistically significant absorption feature. This points to the existence of an EUV attenuating cloud at ≈ 62 pc in the general direction of $l = 165°$, $b = -32°$, which is also visible in the IRAS survey data and is coincident with a complex of nearby MBM clouds. Although shadowing by molecular clouds has previously been detected in soft X-rays (e.g., Burrows and Mendenhall 1991), this is the

first observation at EUV wavelengths and is the first direct evidence for a diffuse astronomical background in the EUV.

3 Conclusion

From these preliminary science results it is clear that much work remains to be done by the EUVE satellite. It is clear that almost all types of astrophysical objects can be detected at EUV wavelengths, and although most future observations will concentrate on our nearest neighbors in the galaxy, it is truly remarkable that the realms of extragalactic objects are also available for observation. Hence, over the next years of operations I am convinced that EUVE will make an indelible mark in our understanding of high temperature astrophysical plasma in many differing types of galactic and extragalactic objects.

Acknowledgements

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