The Spectroscopy of Plasma Evolution from Astrophysical Radiation (SPEAR) Mission

Jerry Edelstein[a], Eric J. Korpela[a], Barry Y. Welsh[a] ,
Kyoung Wook Min[b], Wonyong Han[c], Uk-Won Nam[c]

[a]Space Science Laboratory
University of California,
Berkeley, CA 94720-7450

[b]Satellite Technology Research Center
Korea Advanced Institute of Science and Technology
373-1 Kusong-dong, Yusong-gu
Taejon 305-701, Korea

[c]Korea Astronomy Observatory
61-1, Hwaam-dong, Yusong-gu
Taejon 305-348, Korea

ABSTRACT

The evolution of hot interstellar medium (ISM) in galaxies is fundamental to the evolution of our cosmos. The Spectroscopy of Plasma Evolution from Astrophysical Radiation (SPEAR) mission will study the hot ISM, providing pointed observations and the first all-sky spectral maps in the Far (FUV) Ultraviolet. The FUV bandpass contains the primary cooling lines of abundant elements in a variety of ionization states. SPEAR's broad bandpass (λλ 900 – 1750 Å), spectral resolution (λ/δλ ~ 700) and imaging resolution (5' – 10') has been chosen to determine independently the quantity, temperature, depletion, and ionization of hot galactic gas. These SPEAR data will allow us to study the hot ISM on both large and small scales and to discriminate among models of the large-scale creation, distribution, and evolution of hot gas in the Galactic disk and halo.

Keywords: Far ultra-violet, spectroscopy, space-mission

1. INTRODUCTION

The SPEAR (Spectroscopy of Plasma Evolution from Astrophysical Radiation) mission, which is scheduled for launch in the second half of 2003, will conduct a sensitive all-sky survey of diffuse far ultraviolet (900-1750 Å) emission from interstellar and intergalactic matter. The primary science objectives of this mission include mapping the flow of mass and energy through the interstellar medium (ISM), mapping the global distribution of the multiphase interstellar medium, and testing contentious models for the origin of the hot interstellar plasma. Secondary goals include a sensitive survey of Galactic diffuse H_2 fluorescence, investigation of interstellar dust properties and distribution, and a search for intergalactic intermediate temperature plasmas.

Correspondence: Email: jerrye@ssl.berkeley.edu; Telephone: 510 642 0599

Future EUV/UV and Visible Space Astrophysics Missions and Instrumentation,
J. Chris Blades, Oswald H. W. Siegmund, Editors, Proceedings of SPIE Vol. 4854 (2003)

We discuss the SPEAR mission and its primary scientific program using broad-bandpass FUV spectroscopy to investigate the global structure and evolution of the multiphase ISM. We also briefly describe a supplemental space physics science program and summarize the instrumentation and mission. SPEAR will be launched as the primary payload on KAISTSAT-4, a multi-year mini-satellite mission conducted by the Korea Advanced Institute of Science and Technology

2. THE SPEAR ASTROPHYSICS PROGRAM

We still know very little about the distribution, state or evolution of hot Galactic plasma. Several models for the origin of this gas have been proposed. SPEAR will constrain the plasma state both globally through its spectral sky maps and locally through observations of individual SNRs and superbubbles. FUV spectra from SPEAR will help us to unravel the complex physics of plasmas cooling from high temperatures: emission features in our 900-1750 Å bandpass and $\lambda/\delta\lambda \sim 700$ resolution will provide a sensitive diagnostic of plasma temperatures in gas between $10^{4.5}$ and 10^7 K. SPEAR will observe the FUV cooling lines of hot IS gas across the entire sky (in a survey) and toward specific IS targets, providing a global characterization of Galactic plasma by mapping its emission with 5' to 10' resolution. This angular resolution enables observation of neutral/hot gas interfaces on the same scale as the best existing neutral gas observations (e.g. infrared and H I radio surveys). The independent sky-map pixels can be binned as desired to facilitate sensitive model comparisons.

The three leading theories of the global ISM, shown in models of the galactic sky in Figure 1, are a cloud-evaporation model, a galactic-fountain model, and a SN bubble model. These models are best characterized by their predictions of the all-sky distribution of O VI (1032, 1038 Å) and C IV (1548, 1551 Å) emission. In the McKee-Ostriker model, the bulk of the FUV emission is produced in conductive envelopes surrounding cool, neutral clouds embedded in a hot plasma matrix. In galactic-fountain models, the ionized gas follows a non-equilibrium thermal evolution as it cools radiatively while cycling between the disk and halo. In the SN model of the ISM, ionized gas is located primarily in evolving SN bubbles randomly distributed throughout the disk. Though dramatically different, these pictures of the sky remain untested.

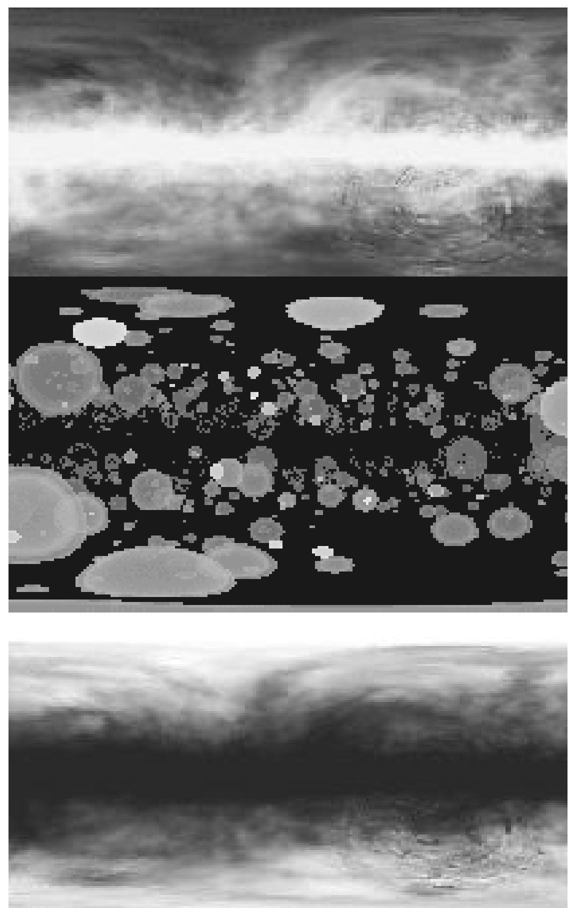

Figure 1. Models of the Galactic FUV sky[4] from a cloud-evaporation model (top), a SN bubble model (center) and a galactic-fountain model (bottom). Brighter regions of sky are lighter. The appearance of the Galactic FUV sky is unknown.

Stars keep the Galaxy "alive" by continuously supplying energy through radiation, stellar winds, and SN explosions. SN explosions are the major source of energy for the hot coronal gas and the kinetic energy of the moving clouds. Supernovae together with stellar winds, can produce gigantic hot bubbles surrounded by dense shells, called "superbubbles" and "supershells" that may break through galactic disk to form "chimneys" venting hot gas "halo". SPEAR will study the role of superbubbles in the Galactic halo. Highly-ionized FUV emitting gas may still exist in "inactive" superbubbles and chimneys, whose interiors are no longer heated by recurrent supernovae. SPEAR observations of shocks will provide empirical information on, for example, the importance of cloud sizes and geometries. There are more than 200 known SNRs in the Galaxy . These objects are bright in the FUV and large on the sky. In survey mode, SPEAR is predicted to obtain spectra of bright SN with signal to noise of ~ 20 in each 5' – 10' imaging pixel. With its 8^{o}x5' field of view, SPEAR can produce a detailed FUV spectral map across the full extent of a nearby SNR in a single observation.

SPEAR will observe molecular hydrogen fluorescent emission and dust scattering in the diffuse ISM. Molecular clouds, consisting mostly of H_2, play an important role in the flow of mass and energy through the ISM. In a continuous exchange of matter, the ISM coalesces into the molecular clouds that collapse to form new stars. Dust grains affect energy exchange in the ISM and obscure extragalactic radiation. Dust properties in a variety of galactic environments must be determined to understand these effects fully. Dust grains scatter and absorb FUV starlight and re-emit the energy at IR wavelengths, but the majority of incident photons are scattered. The amount of FUV radiation is, therefore, one of the crucial quantities determining the physical and chemical evolution of the ISM. SPEAR will map the diffuse galactic light to derive the scattering properties of dust in diffuse IS clouds.

Recent cosmological simulations have predicted that 30-40% of the total baryons in the universe may be located in the warm-hot intergalactic medium with temperature between 10^5 and 10^7 K, located between clusters of galaxies in filamentary structures. SPEAR will observe gas of this temperature in the FUV band.

3. THE SPEAR SPACE PHYSICS PROGRAM

As a secondary science program SPEAR, together with other space physics instruments on K-4, will conduct a space physics science program by observing the auroral zone and day and night airglow. SPEAR will be the first instrument to return high-resolution FUV imaging spectra of the aurora together with simultaneous in-situ plasma physics measures. The airglow observations will also be beneficial to the astrophysics observations as they provide a mean to identify and remove potential contaminants from weak airglow lines. The SPEAR spectrograph bandwidth includes the important Lyman-Birge-Hopfield (LBH) emissions that will provide information on the total precipitated electron flux and average energy of electrons in an aurora. A fundamental question that can be addressed by these measurements concerns the physics of ionosphere-magnetosphere coupling, how a quiet arc breaks up and evolves into complex and dynamic structures near the local midnight region.

4. SPEAR PERFORMANCE CAPABILITY

There have been few attempts to measure diffuse FUV emission, and in only a limited number of sight lines has it been detected. Current observatory efforts with FUV measurement capabilities (e.g., *Copernicus, IUE,* HUT, *ORFEUS,* GHRS, STIS, *FUSE*, *GALEX,* COS) are optimized for point sources. These instruments are not capable of sensitive spectral measurements of diffuse IS emission over the angular scales needed to characterize the galactic plasma distribution: they suffer inadequate spectral or spatial resolution; are unable to correct for noise sources such as intense geocoronal emission, bright stars and dust-scattered stellar continuum; or have insufficient mission or integration periods. Few observations of FUV emission from the ISM exist. Martin & Bowyer (1990) detected C IV 1550 Å and O III] 1665 Å interstellar emission with intensities of several thousand LU toward four of eight sight lines observed. These widely-referenced results provide key constraints on each of the global ISM models discussed above, yet they represent only a few lines of sight. O VI emission has proven difficult to observe. Recent results from FUSE include the detection of Galactic OVI emission in several high galactic latitude fields with a doublet intensity of ~5000 LU (Dixon et al 2001, Shelton et al 2001). We note that although FUSE observations of OVI required long exposure times (20-200 ksec), SPEAR will measure a similar O VI intensity over its field in as little as 150 s.

SPEAR will provide comprehensive and detailed FUV emission measurements, with sensitivities an order of magnitude better than the few existing FUV emission detections and sufficient for testing the predictions of global ISM. In a 12 ksec pointed observation (approximately one day on orbit), SPEAR is predicted to achieve a 3σ sensitivity to the O VI doublet of 260 LU over its full field of view, which is 5'x4^{o} or 0.33 square degrees for the instrument's short-wavelength channel. The corresponding sensitivity to the C IV doublet is 170 LU over the long-wavelength channel's 5'x8^{o} field of view. In survey mode, a 3^{o}x3^{o} sky pixel will achieve 3σ sensitivities of 1035 LU in O VI and 660 LU in C IV in 760 s, the average integration time on the sky. Improved sensitivity limits can be achieved simply by binning the survey into larger sky pixels: for example, 6^{o}x6^{o} pixels yield twice the sensitivity of 3^{o}x3^{o} pixels. In both survey and pointed modes, SPEAR can detect the emission predicted by each of the models at S/N levels of 4–20.

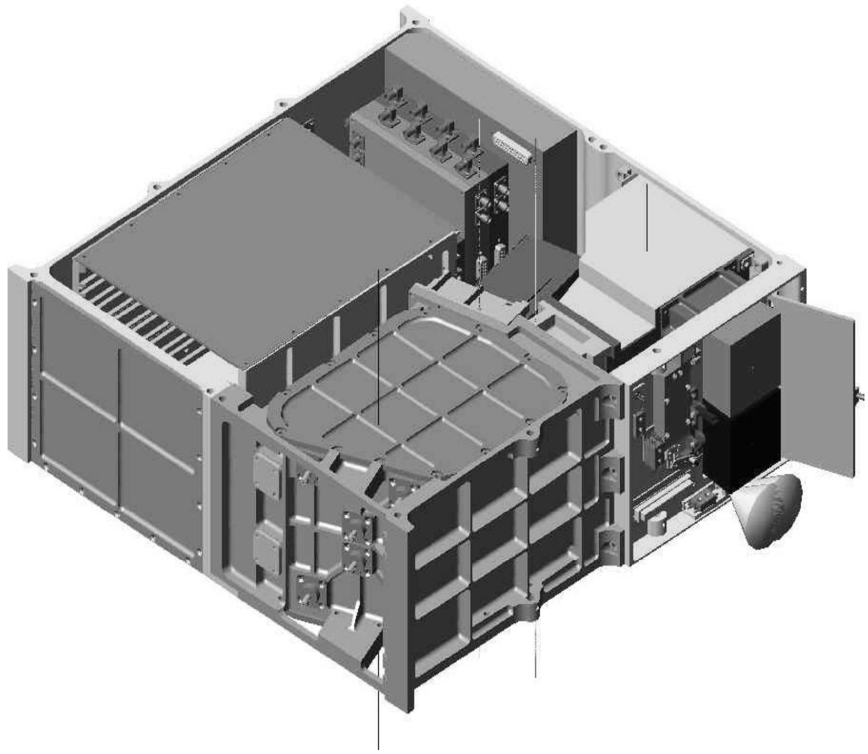

Figure 2. The SPEAR Payload contains an evacuable enclosure holding diffractions gratings and a detector (front center), a shutter unit attached to the mirror housing and contamination cover (shown open, right), analog and power electronics units (rear center), and an electronics assembly (left). The dual channel fields of view are shown (square protrusions, right) as is the sun-avoidance sensor view (cone, right). The payload size is 45 x 45 x 15.5 cm.

4. THE SPEAR INSTRUMENTATION & MISSION

The SPEAR instrumentation is described in more detail by Korpela, et.al (2002), Ryu, et al (2002) and Rhee, et. al (2002). SPEAR is a dual imaging spectrographs, optimized for faint diffuse radiation. The optical system focuses plane-parallel light from infinity to a view defining slit using a parabola of translation collecting mirror. The cylindrical wave from the slit illuminates a grating that is an ellipse of rotation with constant rulings that focus the light in both imaging an spectral space. SPEAR has bands with identically figured optics and a shared slit and detector plane. Its Short λ channel (Sλ) covers $\lambda\lambda$ 900 – 1175 Å and its Long λ channel (Lλ) covers $\lambda\lambda$ 1335 – 1750 Å. The channels include the important O VI 1035 Å and CIV $\lambda\lambda$1550 Å multiplets. The field of view is 4^{o} x 5' for Sλ and 8^{o} x 5' for Lλ with 5-10' imaging resolution along the slit. Extreme care has been taken to mitigate the airglow, stellar and instrumental noise sources that often plague FUV measurements.

The SPEAR observations are made through a series of filters designed to isolate the instrumental and scattered-light components of the background. For the pointed observations, the separate data sets are arithmetically combined to produce a background-subtracted spectral image, then flux and wavelength calibrated to produce the final data product. Where applicable, spectra of individual objects are extracted and archived. For the sky maps, star removal is performed at the full imaging resolution of the instrument. Data from regions around known FUV-bright stars will be excluded. FUV-bright stars require special consideration, particularly during the sky-survey phase. Stars can conceivably affect the performance of SPEAR. About 15,000 stars, mostly in the plane of the galaxy, will be detectable in sky-survey resolution elements. By using our restart scheme, the total integrated data loss due to stars is less than 2% with, for example, no more than 3% of all 3x3 degree sky map bins suffering more than 10% data loss. An interesting product of the SPEAR sky survey will be FUV spectra for ~5000 stars with SNR>10 per spectral element. These data will be of use in estimating the interstellar radiation field. The maps obtained through individual filters are combined as above to produce background-subtracted rate maps, then flux and wavelength calibrated to produce the final data set. Our final data product will be a pair of intensity maps, one per detector, consisting of a 1024-pixel spectrum at each position on the sky, in 0.15°x 0.15° bins. The SPEAR sky-maps and pointed data will be placed in the public archive after a calibration / proprietary period.

SPEAR is scheduled for launch in the second half of 2003 as a secondary payload on COSMOS. The orbit is ~800km altitude and sun-synchronous with at 25 minutes or more of eclipse per eclispe. The mission plan is to conduct a full sky-survey in the first mission year by sweeping 180 degrees from ecliptic pole to pole each night. Pointed observations follow, averaging 1 target per mission day, in the following year. Calibration targets (stars) will be observed on a regular and repetitive basis. Survey sky coverage and exposure were derived from a mission analysis, considering the orbit, slew rate, SAA avoidance, and star-tracker limitations. The sky exposure follows a cosine law with a minimum effective exposure in the ecliptic plane (450 sec) and a maximum exposure at the ecliptic pole (~17,000 sec). In astronomical units, these intensities correspond to ~ 0.0001 EM (cm^{-6} pc), or in physical units ~$3x10^{-9}$ $erg/s/cm^2/sr$. In comparison to previous measurements of interstellar FUV emission, SPEAR would detect the *FUSE* and *UVX* measured intensities of 2,300 *LU* of O VI **λλ 1035Å** and 5,000 *LU* of C IV **λλ 1550 Å** with a S/N of 36 and 90, respectively. In similar fashion, for the average sky-map exposure in 4,500 bins of 3°x3° degrees, the *FUSE* and *UVX* intensities would

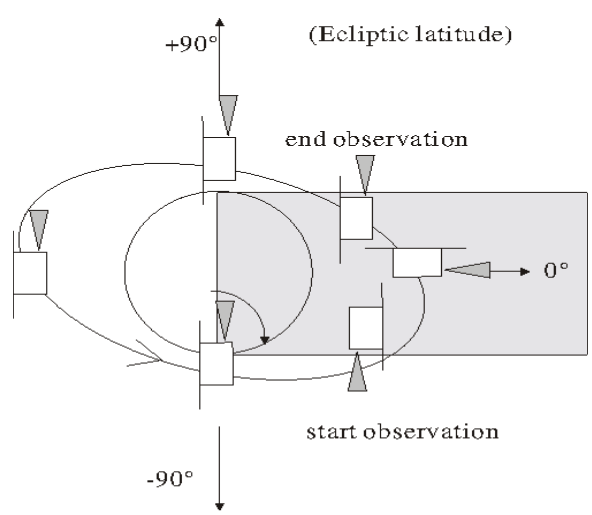

Figure 3. The SPEAR sky survey operation will sweep the field of view over half a great circle in the sky between the ecliptic poles each day for 1 year.

be measured with a S/N of 7 and 23.

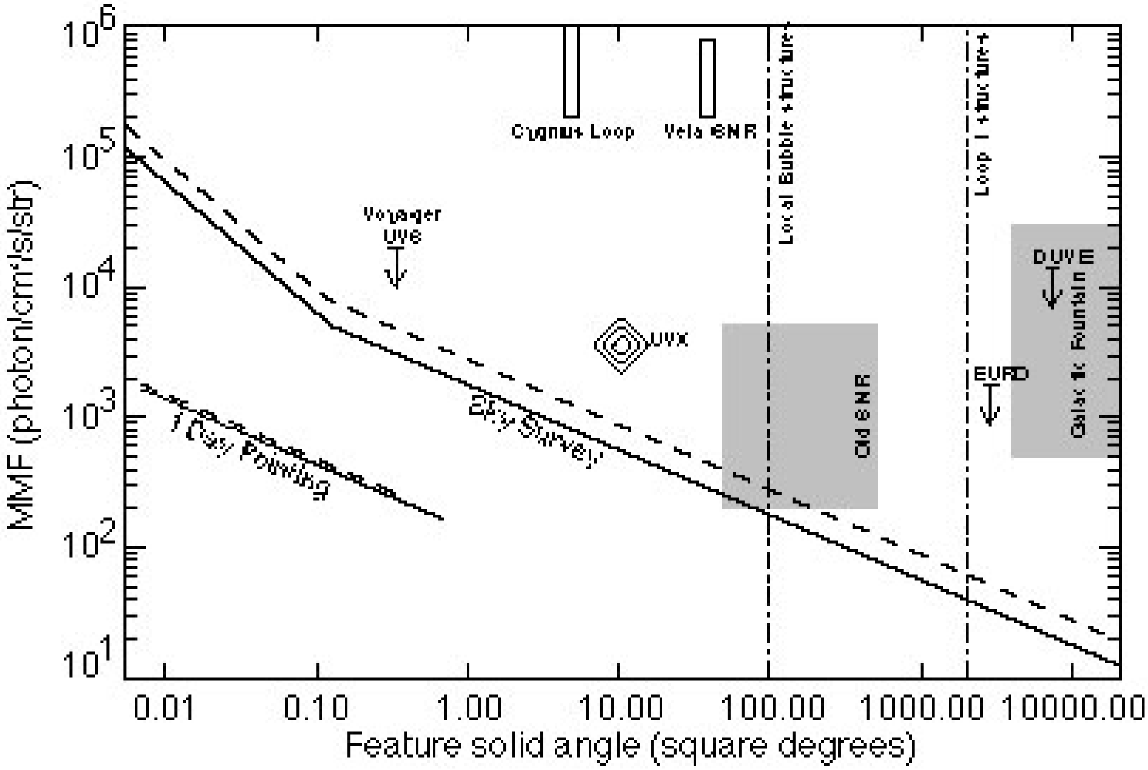

Figure 4. SPEAR Sensitivity vs Integrated Solid Angle**:** The solid lines represent the predicted 3σ MMF of FIMS for the CIV 1550 doublet in the sky survey and in a 1 mission day (12 ksec) pointed observation versus the solid angle over which the signal is integrated. The dashed lines represent sensitivity for the OVI 1032 doublet. Previous instrument have lacked the sky coverage (UVX, Voyager UVS, HUT, FUSE) to reveal the global state of the ISM, or the sensitivity to detect faint interstellar lines (Voyager UVS, DUVE, EURD). The SPEAR sky survey is very sensitive (MMF<500 LU) on scales where interstellar structures such as tunnels in the local ISM, old supernova remnants, signatures of galactic fountains and super-bubbles appear

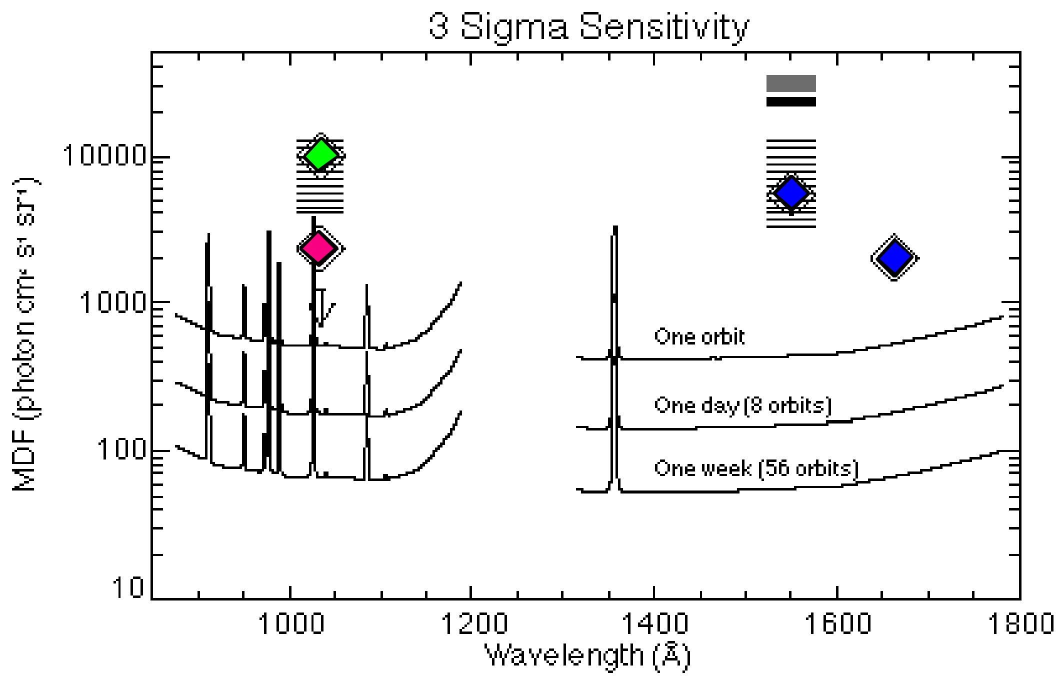

Figure 5. The SPEAR instrument predicted pointed Sensitivity (3σ) for singlet line emission as a function of wavelength over the instrument bandpass. The lines represent one orbit, one mission day (8 orbits of data) and one mission week (56 orbits of data). The diamond symbols represent measurements of OVI (FUSE, HUT), CIV (UVX), and OIII] (UVX) emission. The arrow represents the best upper limit to date of sky-averaged OVI flux (EURD). The shaded regions represent predictions of the galactic fountain models.

ACKNOWLEDGEMENTS

This work was supported by NASA grant NAG5-5335. We thank the Korean Ministry of Science and Technology for their continued sponsorship of the KAISTAT-4 mission and for SPEAR development funding through the Satellite Research Center at the Korea Advanced Institute for Science and Technology, and through the Korea Astronomy Observatory. We thank the SPEAR team at Space Sciences Lab and the FIMS team at SaTReC and KAO for their great work.

REFERENCES

1. Korpela, E., *etal*., "The SPEAR Science Payload", *Proc. SPIE*, **this volume** (2002)
2. Rhee, J.G., *eta.l*, "The Microchannel Plate Detector Electronics System for SPEAR", *Proc. SPIE*, **this volume** (2002)
3. Ryu, K.s., *etal*,"Optics Development for the SPEAR Mission", *Proc. SPIE*, **this volume** (2002)
4. Korpela, E., Bowyer, S. Edelstein, J., "Spectral Observations of Diffuse Far-Ultraviolet Emission from the Hot Phase of the Interstellar Medium with the Diffuse Ultraviolet Experiment", *Astrophysical Journal*, **495**, p.317 (1998)