THE “SPECTROSCOPY OF PLASMA EVOLUTION FROM ASTROPHYSICAL RADIATION” MISSION

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ABSTRACT

The “Spectroscopy of Plasma Evolution from Astrophysical Radiation” (SPEAR, also known as the “Far-Ultraviolet Imaging Spectrograph”) instruments, flown aboard the STSAT-1 satellite mission, have provided the first large-area spectral mapping of the cosmic far-ultraviolet (FUV; 900–1750 Å) background. We describe the mission and its science motivation, the mission data and their processing, and the effects of mission performance on the science data. We present the first map of the cosmic FUV background (1360–1710 Å) over most of the sky as an example of the mission results. These SPEAR data reveal diffuse radiation from warm and hot (10⁴–10⁶ K) plasma, molecular hydrogen fluorescence, and dust-scattered starlight. They allow for an unprecedented characterization of the spectral emission from a variety of environments, including the general interstellar medium (ISM), molecular clouds, supernova remnants, and superbubbles.

Subject headings: ISM: general — ultraviolet: ISM

1. INTRODUCTION

The “Spectroscopy of Plasma Evolution from Astrophysical Radiation” instruments (SPEAR, also known as the “Far-Ultraviolet Imaging Spectrograph” or FIMS) have provided the first large-area spectral sky survey of cosmic far-ultraviolet (FUV) radiation. The FUV band (900–1750 Å) includes important astrophysical diagnostics such as strong cooling lines from warm and hot (T = 10⁴–10⁶ K) and photoionized plasmas, as well as radiation from molecular hydrogen (H₂) fluorescent emission and dust-scattered starlight.

SPEAR is the primary payload on the STSAT-1 (S-1) satellite, launched 2003 September 27. The mission has thus far observed ~80% of the sky and conducted deep pointed observations toward numerous selected targets. SPEAR contains dual imaging spectrographs optimized for the measurement of diffuse FUV emission. The spectrographs, referred to as the “Short” wavelength band (“S”; 900–1150 Å, 4.0 × 4.6 view) and “Long” wavelength band (“L”; 1350–1750 Å, 7.4 × 4.3 view), each have a spectral resolution of λ/Δλ ~ 550 half-energy width and an imaging resolution of 5′. Each instrument uses a collecting mirror, a diffraction grating, and a photon-counting microchannel-plate detector. The SPEAR instruments, their on-orbit performance, and processing of the instrument photon data are detailed in the following Letter (Edelstein et al. 2006).

In this Letter, we describe the SPEAR mission and its science objectives, the mission data and their processing, and the effects of mission performance on the science data. Mission performance issues include noninstrumental factors that affect the ultimate science return, such as observing modes, pointing and aspect determination, and sky coverage. The mission operational performance is demonstrated by a presentation of the first mapping of the cosmic FUV background (1360–1710 Å) over most of the sky. We then provide a brief introduction to the SPEAR science results presented in the accompanying Letters of this issue.

2. FAR-ULTRAVIOLET EMISSION FROM ENERGETIC PLASMA IN THE INTERSTELLAR MEDIUM

Supernovae and stellar winds produce shock-heated gas in the Galaxy. The activity powered by the energetic plasma shapes the structure of the Galaxy, affecting the distribution of metals and driving evolutionary phenomena such as star formation that depend on global morphology. On smaller scales, hot gas can power a variety of radiative, mechanical, and chemical phenomena by forming turbulent and evaporative structures, altering chemical abundance by means of dust ablation or vaporizing dust condensates, and radiatively influencing the gas ionization balance. Candidate mechanisms (see McKee [1995] for an overview) by which interstellar plasmas cool include (1) energy exchange with surrounding media, such as evaporation and conduction, (2) mechanical cooling such as adiabatic expansion, (3) direct emissive radiation, and (4) indirect radiation by way of heated dust grain emission. Our understanding of shock-ISM interactions and the global structure of ionized gas in our Galaxy are far from complete. Several models for the origin of this ionized gas have been proposed (Slavin & Cox 1992, 1993; Shapiro & Benjamin 1991; Borkowski et al. 1990; Shelton 1998) that make distinctive predictions about the population of warm and hot material and would result in different absorption and emission signatures, yet none can be ruled out with current observations.

Very hot interstellar diffuse gas (T ≥ 10⁶ K, first mapped by experiments on sounding rockets (see McCammon et al. 1983) and later observed in detail with ROSAT soft X-ray (SXR) background observations (Snowden et al. 1998), show pervasive regions of SXR gas at high latitudes conceivably caused by hot gas injected into the Galactic halo, although uncertainty remains regarding the state of this gas. A component of this SXR emission has been attributed to local hot gas, but charge exchange between the solar wind and the heliospheric environs

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may confuse the observations by producing the same detected species (Lallement 2004; Wargelin et al. 2004). Sanders et al. (2001) and McCammon et al. (2002) have recorded SXR diffuse emission spectra that are inconsistent with predictions of standard models of hot ionized gas, but these data may also be contaminated by solar charge exchange. The Cosmic Hot Interstellar Plasma Spectrometer (CHIPS; Hurwitz et al. 2005) mission’s extreme-ultraviolet (EUV) observations have established upper limits to local hot gas that are an order of magnitude less than expected from the postulated local SXR-emitting gas, unless Fe atoms in the gas that would produce most of the emission lines observable by CHIPS have been strongly depleted onto interstellar dust grains. [EUV observations are limited by interstellar absorption to nearby regions, with N(H i) < 10^{18.5} cm^{-2}.]

The dominant fraction (>85%) of the radiative cooling power from hot, thin interstellar plasma is emitted in the FUV (Landini & Monsignori Fossi 1990). These FUV transitions, from the most abundant ions in prevalent ground states, provide important diagnostics for both collisional and photoionized species. FUV absorption observations have revealed the hot ionized Galactic ISM. Measurements taken with the International Ultraviolet Explorer (IUE) and the Hubble Space Telescope have shown that Si iv, C iv, and N v ions, characteristic of T = 10^{5.5}–10^{6} K gas, exist throughout the Galaxy with scale heights up to 4–5 kpc (Sembach & Savage 1992). Hotter gas, with T = 10^{5.2}–10^{6} K and indicated by O vi λ1032 absorption, has been observed with Copernicus, Voyager, the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS), the Hopkins Ultraviolet Telescope (HUT), and now the Far Ultraviolet Spectroscopic Explorer (FUSE) (Jenkins 1978; Hurwitz et al. 1995; Davidsen 1993; Zsargó et al. 2003). The O vi appears ubiquitous, although patchy in distribution, and perhaps extends to a scale height of several kiloparsecs (Savage et al. 2003). FUV absorption measurements, limited to sight lines with suitable background sources, cannot alone yield the physical state parameters of the hot plasma (e.g., n, T, pressure, filling factor) and are not suited to the detection of lines from gas with a large velocity dispersion, because placement of the adjacent stellar continuum is problematic.

Detection of FUV interstellar emission lines from the ISM has proved to be difficult. Measurements with sounding-rocket experiments, short-lived orbital missions, and small instruments on interplanetary missions have suffered from inadequate spectral or spatial resolution; from an inability to carefully correct for noise sources such as intense geocoronal emission, bright stars, and dust-scattered stellar continuum; or from integration periods insufficient to obtain sensitive results. (See Bowyer [1991] for a review of earlier work.) Space observatories with FUV measurement capability (e.g., Copernicus, IUE, HUT, ORFEUS, the Goddard High Resolution Spectrograph, the Space Telescope Imaging Spectrograph, FUSE) have been optimized for point-source observations and not for measuring faint diffuse spectra over the large angular scales needed to characterize the Galactic plasma. Although the current Galaxy Evolution Explorer (GALEX) mission (Martin et al. 2005) was designed to observe large areas of the sky, it has a limited capacity for mapping Galactic diffuse emission, since it must exclude observations of regions including bright stars. GALEX records either a broadband image including no spectral information or an objective-dispersion image that obtains low-resolution spectra of localized sources but can confuse diffuse sources with angular extent.

Despite these difficulties, the detection of interstellar C iv and O iii] FUV line emission was reported 15 years ago (and not since, until now) (Martin & Bowyer 1990). These lines were observed at intensities of several thousand LU toward four locations, from which the properties of an interstellar component were derived, with n = 0.01–0.02 cm^{-2} and T = 10^{6.7}–10^{7.2} K (Shull & Slavin 1994). Emission from interstellar O vi has been convincingly detected more recently, with a doublet intensity of ∼3000–5000 LU toward a dozen targets, using long (20–200 ks) FUSE observations of 30° fields (Dixon et al. 2001; Welsh et al. 2002; Shelton et al. 2001; Otte et al. 2003).

The SPEAR mission was specifically designed to provide a spectral imaging survey of diffuse FUV radiation from the ISM. We report the first extensive spectral observations and detection of such radiation. As described in the accompanying Letters in this issue, these SPEAR data show that diffuse FUV emission lines emanate from atomic, ionic, and molecular species in a variety of interstellar environments.

3. THE SPEAR MISSION: OPERATIONS AND DATA

SPEAR, aboard the S–l satellite, was injected into a 700 km Sun-synchronous orbit at 98°2 inclination with an orbital period of 98.5 minutes and a ∼34 minute eclipse. Observations are scheduled to begin ∼360 s after eclipse entry and end ∼300 s before eclipse exit. About 10 daily orbits are scheduled for astronomy observations. One or two orbits per day are used for down-looking observations of the northern nightside aurora. The three-axis–controlled spacecraft platform can use a star tracker to achieve 5′ pointing knowledge, pointed accuracy of ∼6′, and a stability of ∼12′.

Various pointing modes are used for survey, target, and calibration observations. Sky survey observations are performed by rotating a spacecraft axis such that the SPEAR field of view is swept, in a “push broom” fashion, perpendicular to its long field of view and in a 180° great circle from the north to south ecliptic pole via the anti-Sun direction. Following the anti-Sun progression in this way over 1 year would cause a full viewing of the sky with a maximum of overlapped exposure at the ecliptic poles and a minimum of exposure at the ecliptic plane. Calibration observations of stars or small (≤10′) fields are performed by a “back and forth” spacecraft rotation that sweeps the field of view over a limited angle. The calibration pointing mode, together with reports of the spacecraft roll rate and the ground-measured width of the view field, provides the most accurate positional data and exposure times for the observation of point sources. Fixed inertial pointing toward specific targets can also be performed. Pointings avoid the Sun by 45° and the spacecraft velocity vector by 60° and are limited to zenith angles of less than 110°.

The SaTRec Mission Operations Center, Daejeon, Korea, is used to control the mission and receive data. Data are de-commutated into spacecraft-time–marked attitude and SPEAR-time–marked science and engineering information. The information is passed through a photon reduction processing pipeline (Edelstein et al. 2006) that performs (1) engineering selection of valid photon events, (2) correction of detector electronic drift, (3) transformation from detector to physical coordinates, (4) correction of detector distortions, and (5) marking of photons with Universal Time. A mission data process-
ing pipeline creates (1) a time history of attitude knowledge, (2) a SPEAR-to-spacecraft time association history, (3) a time-associated sky exposure history, and (4) photon lists with time-associated attitude information. The mission data products, in concordance with the photon data products, can then be combined to produce fluxed spectra and spectral sky maps.

Each photon event is mapped to the sky by using a combination of the spacecraft attitude information, the instrument boresight offset from the spacecraft axis, and the angular position of the event on the detector. Absolute boresight is determined by correlating reconstructed sky images with a field of known bright stars. The spacecraft attitude knowledge, scheduled for report at 1–2 s intervals, is determined by a star tracker and a gyroscope. The tracker updates are designed to set the gyro knowledge to ∼2'' accuracy every 5 s. The gyro knowledge drifts at 0.2 s⁻¹. The knowledge error, derived from the drift rate and tracker update history, is assigned by the pipeline processing for each photon. The sky location at times in between spacecraft attitude reports is computed using a spherical coordinate interpolation.

Sky exposure is derived according to valid exposure intervals (typically 60 s) that are determined by examining operational and telemetry-interruption markers interleaved with the photon data. Time-marked exposure records are produced every 1.0 s within valid intervals for each 5' increment within the spectrometer field-viewing angles. Each exposure event can then be mapped to a sky position in a similar fashion as for photons. Exposure events include a weighting factor to account for fractional-second intervals that may occur at the end of valid periods, for partial coverage of a sky pixel, or for other effects such as processing dead time or angular vignetting (see Edelstein et al. 2006). Time synchronization between the instrument and the spacecraft is based upon an interpolation between spacecraft time reports and a correction that uses precise, synchronized 1.0 Hz and 10 Hz timing marks that have been interleaved with the instrument data stream. The timing correction requires careful handling of clock interruptions or erroneous telemetry. Photon events are marked to a precision of 0.1 Hz with an estimated timing accuracy of 0.25 s. Events with indeterminate time synchronization or shutter position, usually due to corrupted and missing telemetry, are eliminated and correspond to ∼2% of the data.

3.1. Mission Performance

The SPEAR observational results depend on mission performance parameters including sky coverage, sky exposure, and mapping accuracy. We report on the first year (2003 November to 2004 November) of observations. The S-I mission was designed for a 2 year mission; however, spacecraft engineering problems may preclude further science observations. During the first year, 2450 orbits of observations were recorded. The S-I attitude control system behavior limits the quality of attitude-knowledge reconstruction. We find that the boresight offset is not constant on a per-orbit basis, because of a variation in the reporting of attitude. Furthermore, the star-tracker updates are sometimes lost, resulting in an attitude error caused by gyro drift. Finally, especially toward the end of the year, star-tracker updates or attitude-knowledge reports are less frequently available. While about 40% of our data suffer from some form of these problems, we have created successful schemes to recover high-quality data.

The precision of attitude reconstruction from multiple, overlapping sky viewings is affected by the attitude system stability. We have developed a systematic approach that uses SPEAR itself as a star tracker to correct for boresight variability in survey and calibration sweeps. This method has been applied to the observation of individual targets and to ∼850 survey-sweep orbits. For observations that cycle sweeps over one field, the attitude timing delay is varied until L-band stellar images converge. Absolute boresight is then determined by using a two-dimensional correlation of the image to bright 1565 Å stars listed in the TD-1 catalog (Carnochan & Wilson 1983). For survey or other single-sweep observations, a similar correlation is used between TD-1 catalog objects and the L-band sweep image, recomputed for variable timing delays. The image of a single star can be reconstructed from multiple viewings to an effective resolution of 10’ FWHM with a 10’ positional accuracy. Survey-sweep positional corrections in the sweep track direction are found to be ∼30’ (2σ) and ±8’ (3σ) in the cross-track direction. Because the S-I attitude follows a time-sequenced command program, SPEAR can produce an image of a sweep-observed region even when attitude knowledge is compromised or absent. We anticipate that the attitude knowledge for a large fraction of the data with yet-uncorrected attitude problems can be improved with further work.

4. OBSERVATION OF THE DIFFUSE FAR-ULTRAVIOLET SKY

We derive a spectral sky map of diffuse FUV radiation from these data. The map shows the SPEAR mission sky coverage and the ability to map detected photons to their correct sky origin. Spectral sky maps were created by binning photon and exposure events using the HEALPix tessellation scheme (Górski et al. 2005) with ∼15’ pixels and L- and S-band wavelength bins of 1.0 and 1.5 Å, respectively. The data were selected for attitude-knowledge quality by using times when the derived attitude error is ≤30’ and contain 1.2 × 10⁶ and 1.4 × 10⁷ photons for the L and S bands, respectively. The corresponding sky exposure map for the L band, shown in Figure 1, covers ∼80% of the sky and includes features such as deep exposures (>10 ks) toward calibration and pointed study fields and exposures of over 500 s deg⁻² near the north ecliptic pole, where many survey sweeps overlap. About 15% of these observations were taken using the 10% shutter aperture. Apparent are regions where no coverage exists, due to the aforementioned attitude problems, to operational interruptions, and to detector-protective shutdowns while observing FUV-intense regions such as the Galactic plane. The integrated exposure for the instantaneous field of view is 987 ks, with an average of 65 s deg⁻² for observed sky regions. The S-band exposure map

Fig. 1.—Sky exposure for the SPEAR L-band observations. The map is made with 0.5 pixels and a histogram-equalized intensity scale with a maximum of 500 s deg⁻². Galactic Aitoff coordinates centered at (l, b) = (0°, 0°) with longitude increasing toward the left are shown with latitude and longitude lines on a 30° grid.

No. 2, 2006 SPEAR MISSION L155
is similar to the L-band map, although coverage is reduced because of the smaller field of view.

In order to obtain a true image of the cosmic FUV sky, these data were subject to further reduction to account for artifacts due to mission factors, for example, orbital position and environment and spacecraft attitude and time-history errors. Many of the artifacts are evident when simply dividing the photon map by the exposure map. We proceed with artifact removal and analysis of the SPEAR L-band map, for 100% shutter-position observations, because these data have superior coverage and sensitivity in comparison with the S-band data. The artifacts—for example, streaking in the direction of survey sweeps and localized overintense regions—are due to systematic errors in exposure determination and to the recording of data during times of high airglow or radiation background contamination. Overintense regions due to erroneous mapping were eliminated by only including orbits that contain exposure re-
tamination. Overintense regions due to mission factors, for example, orbital position and environment and spacecraft attitude and time-history errors. Many of the artifacts are evident when simply dividing the photon map by the exposure map. We proceed with artifact removal and analysis of the SPEAR L-band map, for 100% shutter-position observations, because these data have superior coverage and sensitivity in comparison with the S-band data. The artifacts—for example, streaking in the direction of survey sweeps and localized overintense regions—are due to systematic errors in exposure determination and to the recording of data during times of high airglow or radiation background contamination. Overintense regions due to erroneous mapping were eliminated by only including orbits that contain exposure re-

To achieve the objective of measuring the diffuse cosmic background, we have developed a simple method to remove the brightest local sources, for example, resolved stars, from the map. Because the FUV diffuse intensity is found to vary by orders of magnitude across the sky, bright sources must be identified as locally intense pixels. To improve the star detection sensitivity, an L-band total intensity map, integrated over 1360–
1710 Å, was adaptively binned by sky area to attain a statistical signal-to-noise ratio value S/N ≥ 45 for each bin. In this scheme, the sky-bin size is increased along HEALPix pixel boundaries, that for contiguous pixel groupings of size 4°, until sufficient counts exist within the bin. In this way, bright objects retain small angular dimensions while faint regions are averaged to larger angular dimensions with values of improved significance. Bright objects were identified in ~3% of the pixels as having an intensity that exceeds 2.5 times the median value of the enveloping 4° × 4° region (256 HEALPix bins). The choices for the adaptive binning S/N and the median factor thresholding parameters were optimized by maximizing the correlation of the 5000 brightest 1565 Å TD-1 catalog (Car-nochan & Wilson 1983) stars and a test map of the detected bright objects. A few thousand bright objects identified in the SPEAR map in this way correspond to TD-1 stars. (We did not attempt to identify stars using point-spread function detection schemes in this preliminary work, because the mapped point-spread function at each point in the sky is a complex composite of the elliptical instrumental spread function, whose orientation differs for each sweep direction.)

The first Galactic map of total diffuse FUV (SPEAR L band) radiation was obtained by eliminating the locally intense pixels (i.e., the bright sky) from the starting continuum map and then adaptively binning the remaining pixels to S/N ≥ 10. The remaining faint-sky map has a 1360–1710 Å band median intensity of 2300 CU that contains a combination of a true cosmic signal including diffuse interstellar emission, interstellar dust-

![Fig. 2.—Total diffuse intensity map of the sky for the SPEAR L-band (1360–1730 Å) observations, after removal of locally intense pixels (stars). The map is in the same coordinate scheme as Fig. 1 and is adaptively binned by sky area to S/N ≥ 10. The intensity scale is linear across the color bar, with a maximum of 20,000 CU. Evident features include the Galactic plane, the Sco-Cen association [e.g., ζ Oph at (l, b) = (6°, 24°)], and the LMC at (l, b) = (280°, −32°). Some artifacts remain, particularly in low-exposure regions.](image-url)
scattered starlight, and direct starlight from unresolved objects, as well as residual instrumental background. A spectral fitting method, described in the following Letter by Korpela et al. (2006), indicates that the instrumental background contributes ~20% of the total faint-sky signal. The bright sky has a band median intensity of ~30,000 CU.

The faint-sky map (see Fig. 2) shows that the mission data can be used to successfully map interstellar FUV radiation from the sky. The largest diffuse intensity is toward the Galactic plane and other regions where bright early-type stars coexist with significant columns of interstellar dust, such as the obvious features of the Sco-Cen association and the Large and Small Magellanic Clouds. Thus, the cosmic FUV flux distribution is consistent with what is generally believed to be its dominant component, starlight scattered by interstellar dust (Bowyer 1991), and is therefore by inspection similar to maps of reddening, N(H i), and Hα (Schlegel et al. 1998; Dickey & Lockman 1990; Finkbeiner 2003) because all these maps trace in some way either interstellar dust or the strong (local) FUV radiation fields that are required to produce the dust-scattered FUV continuum.

There exist only a few spectral observations of the diffuse 1200–1800 Å FUV radiation field, data that have been taken over small areas of the sky (see the reviews by Bowyer [1991] and Henry [1991]). Thus, the SPEAR mission has increased the area of the spectrally mapped FUV sky by orders of magnitude. The FUV field has been observed toward a limited magnitude. The FUV field has been observed toward a limited number of moderate-size fields using bandpass imaging instruments, including those taken with the Ultraviolet Imaging Telescope (UIT; Stecher et al. 1992), the Far Ultraviolet Space Telescope (FAUST; Bowyer et al. 1993), and the Space Telescope Imaging Spectrograph (STIS; Brown et al. 2000), although these instruments generally were optimized for point-source observations. The most similar FUV band imaging data to that of the SPEAR L-band faint-sky map is from NUVIEWS (the Narrowband Ultraviolet Imaging Experiment for Wide-Field Surveys; Schminovich et al. 2001), which mapped one-fourth of the sky in FUV radiation (λ = 1740 Å, Δλ = 100 Å FWHM), including features such as the Upper Scorpius region. We observe that the SPEAR faint-sky map is consistent with the NUVIEWS partial sky map. The SPEAR faint-sky intensity is generally brighter (20%–50%) than the NUVIEWS map, a fact that we attribute in part to our preliminary method of direct starlight removal and in part to our accounting of the detector background.

5. SPEAR SCIENCE RESULTS

We introduce scientific findings that are presented in the accompanying Letters of this issue that are based upon SPEAR data. These Letters detail the identification and importance of observed FUV spectral components in different interstellar environments.

5.1. The Diffuse ISM

Korpela et al. (2006) present SPEAR S- and L-band spectra of the north ecliptic pole (NEP) region [β = +30°, N(H i) ~ (2–8) × 10²⁰ cm⁻²], a region that has no obvious associations with active interstellar regions and therefore represents a typical sight line through the ISM. A large number of diffuse FUV emission lines are detected toward the NEP, which include emission lines also reported toward other interstellar SPEAR targets. Emission lines found that are likely to originate from the warm/hot ISM include the pronounced C IV λ1549 feature and the O IV/σ/n σ(1400 + 1403) blend, previously detected and tentatively identified toward other lines of sight by Martin & Bowyer (1990) at similar intensities, and the O VI λ1032 feature previously seen in FUSE observations as discussed earlier. Interstellar diffuse lines newly discovered with SPEAR include the C iii λ977 and He ii λ1640 features, also likely to originate from the warm/hot ISM. Korpela et al. (2006) find that the lines of high-ionization species cannot be fitted by a collisional ionization equilibrium plasma model even though these ions, modeled on a per-species basis, have consistent emission measures with each other. Therefore, it appears that photoexcitation, nonequilibrium effects, or abundance variations are important in any explanation of the spectrum.

Other discovered lines, which could originate from either neutral or warm ionized ISM, include the Si ii* λ1533 and Al ii λ1672 resonance lines and the N ii λ1085 line. The Si ii* excited-state transition is optically thin in typical interstellar conditions and therefore provides a useful alternative to the ground-state transition for studying low-ionization gas in the ISM. The Al ii λ1671 resonance transition, likely to be optically thick in the typical ISM, does not have an alternate excited state analogous to Si ii*. Also discovered with SPEAR is diffuse 1657 Å and 1561 Å emission from C i, a species that exists in the ISM despite photoionization by the FUV background (Jenkins & Tripp 2001). In addition, substantial H₂ fluorescence emission is detected in the NEP despite the moderately low N(H i) in the region.

5.2. FUV Hydrogen Fluorescence and Continuum

SPEAR observations show that interstellar FUV H₂ fluorescence is ubiquitous, consistent with FUV absorption observations (Shull et al. 2000; Gillmon et al. 2006) that find H₂ over large portions of the sky. The FUV H₂ fluorescence emission, previously detected by Martin et al. (1990), presents prominent and recognizable features (Black & van Dishoeck 1987) in the SPEAR spectra, particularly at 1608 and 1580 Å. Lee et al. (2006) observe H₂ fluorescence in the Taurus cloud halo but not from the dense cloud core, a fact attributed to the core opacity’s excluding the FUV radiation needed to induce fluorescence. Ryu et al. (2006) find H₂ fluorescence emission over a large region about the Orion-Eridanus superbubble and are able to elucidate the geometry of the Ori-Eri region by comparing the FUV fluorescence with Hα and reddening maps. They find, by comparing with model calculations, that the H₂ excitation in this region requires temperatures of over 1000 K, higher than generally found for molecular gas in the Galactic disk. The H₂ fluorescence is also found in deep SPEAR observations of the interface between the Ori-Eri superbubble and the ambient ISM (Kregenow et al. 2006).

The SPEAR observation of the Taurus cloud (Lee et al. 2006) shows a countervuitive anticorrelation of FUV continuum with visual extinction and IR dust emission. The FUV continuum map of Taurus provides an optical transfer relation over a wide range of depths that can be used to quantify the dust and illumination properties—the cloud core appears to block more distant FUV flux, while the cloud halo scatters local flux toward the observer.

5.3. Supernova Remnants and Superbubbles

SPEAR data provide unique spectral images of two nearby and well-studied supernova remnants (SNRs), the Vela SNR...
(Nishikida et al. 2006) and the Cygnus Loop SNR (Seon et al. 2006). Both Nishikida et al. and Seon et al. find that the spatial distribution of FUV luminosity cannot be simply predicted using visible Hα or X-ray emission maps. The remnant emission-line images, recorded in C iv, O iii], C iv, and O vi FUV lines, show where radiative shocks with velocities ranging from \(100\) to \(200\) \(\text{km s}^{-1}\) prevail. The work directly verifies that the FUV emission lines are important to SNR cooling. For Vela, the combined luminosity of strong FUV lines exceeds the \(1.0–4.0\) keV X-ray luminosity by an order of magnitude, with \(\sim\)\% showing where radiative shocks with velocities ranging from \(100\) to \(200\) \(\text{km s}^{-1}\) prevail. Kregenow et al. (2006) report on SPEAR spectra imaged across the shell-wall boundary surrounding the Ori-Eri superbubble, an X-ray–emitting interstellar cavity that may have been created by SNRs or stellar winds. The FUV spectra are rich and include lines of similar species and intensities as found in the all-sky spectrum and in the NEP (Korpela et al. 2006). Kregenow et al.'s analyses show a distinct correspondence of O vi, C iv, and Si ii* with the shell-wall interface traced in Hα, providing unprecedented diagnostics for the study of this type of evolved structure. They show that the boundary emission may be explained by a quiescent thermal interface between the hot cavity X-ray–emitting gas and surrounding cooler interstellar gas and is not necessarily the result of a fast-moving SNR shock wave.

### 6. CONCLUSION

The SPEAR mission and data have provided the first FUV spectral imaging survey of a large fraction of the sky. The resulting map shows that diffuse FUV cosmic radiation is concentrated where both hot stars and scattering dust coexist, such as in the Galactic plane, young stellar associations, and the Magellanic Clouds. SPEAR observations presented in the following Letters show that diffuse FUV emissions, including the previously observed C iv and Si iv and the newly detected C i, Si ii*, and Al ii emission, are found in the general ISM, as sampled at the NEP, and toward the Ori-Eri superbubble and its bounding interface. Intense FUV emission lines from shocks are also visible in nearby SNRs, and diffuse Hα fluorescence is found to be ubiquitous across observed Galactic environments. Much work remains to produce FUV spectral line and continuum sky maps that will allow elaboration upon the character of the FUV sky.

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