1999 VULCANO MEETING
Memorie della Societa Astronomica Italian, eds. F. Giovannelli and L. Sabau-Graziati, **73**, No. 3, pp. 67-75, 2002

COSMIC BACKGROUND RADIATION

RICHARD C. HENRY
Center for Astrophysical Sciences
Henry A. Rowland Department of Physics and Astronomy
The Johns Hopkins University
Baltimore, Maryland, 21218-2686 USA
henry@jhu.edu

ABSTRACT. I discuss the diffuse background radiation from the universe, elaborating on the description that is given in Henry (1999a). In the present discussion, I lay out the spectrum of the Universe in a somewhat different manner, and I give more detail regarding the visible, ultraviolet, and soft X-ray background observations. The question of units for the display of spectra is discussed further. Also, I present some important details of the design of the Hopkins Ultraviolet Background Explorer (HUBE), that was selected in 1996 as a NASA MIDEX 'Alternate' mission, exhibiting in particular a new method due to W. G. Fastie and K. Peacock for measuring the cosmic diffuse ultraviolet background intensity across the intense solar system Lyman α foreground.

1. Spectrum of the Background Radiation

In my 1999 Vulcano talk, I presented the spectrum of the diffuse background radiation of the universe, as it was about to appear in my paper in the Astrophysical Journal (Letters). The reader should read the present paper in conjunction with that paper (Henry 1999a), because what I am presenting here is supplementary material.

The first such supplement is to present my discussion of units for use in the display of spectra *without* the compression that appears in ApJ Letters, so that the material is much more readable:

If one is interested in *energy content,* the most meaningful units in which to display the spectrum of diffuse radiation are, remarkably enough, *photons* s^{-1} cm^{-2} sr^{-1} nm^{-1}. If there is an *equal* amount of energy present in every logarithmic interval of frequency, then these units have the virtue of assuming *constant* value — as I now demonstrate:

For clarity, I omit "cm^{-2} s^{-1} sr^{-1}" from the units. I use constants $h = 6.6261 \times 10^{-27}$ *erg s* and $c = 2.9979 \times 10^{10}$ *cm* s^{-1}. If we have N *photons* nm^{-1}, then in a 1 *nm* passband we have $Nhc/\lambda_{nm}\ 10^{-7}$ ergs. But

$$\Delta\nu_{Hz} = \frac{-c}{\lambda_{nm}^2 10^{-7}} \Delta\lambda_{nm}$$

So N *photons* nm^{-1} corresponds to

$$N\ photons\ nm^{-1} = Nh\lambda_{nm}\ ergs\ Hz^{-1} = \frac{Nhc}{\nu 10^{-7}} ergs\ Hz^{-1} \equiv I_\nu\ ergs\ Hz^{-1}$$

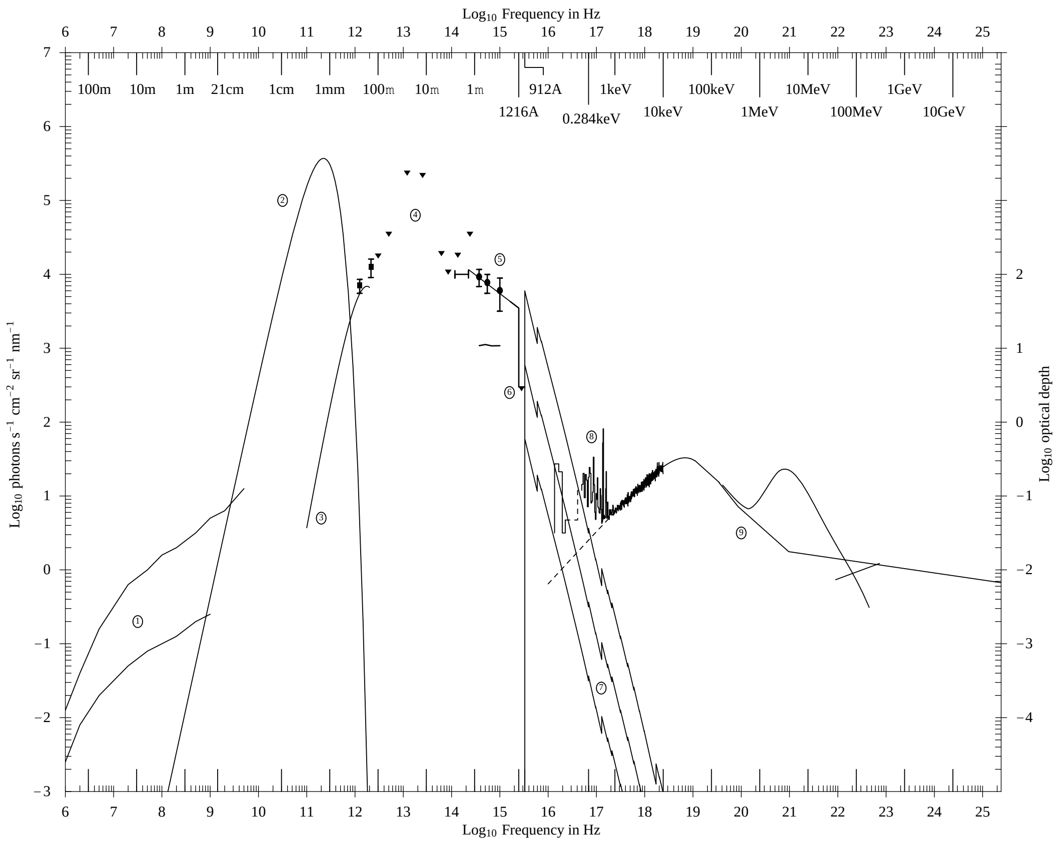

Fig. 1. The spectrum of the diffuse background radiation: 1) radio background, 2) microwavebackground (Fixsen et al. 1994), 3) Firas excess (Fixsen et al. 1998), 4) DIRBE observations and upper limits (Hauser et al. 1998), 5) visible background (Bernstein 1998), 6) background from *Voyager* (Murthy et al. 1999), 7) interstellar photoionization cross-section (use the right-hand scale for this), 8) soft X-ray background, and 9) hard X-ray and γ-ray background. This figure differs from the figure in Henry (1999a) in several respects: only one FIRAS spectrum is shown (instead of observed and $\pm 1\sigma$); instead of actual observations of the soft X-ray background, what is shown here is a simulation of what might be expected from David Burrows' CUBIC experiment (Burrows 1996); and finally, in addition to the new γ-ray background, I show the earlier spectrum that was reported by Fichtel et al. (1978). The short straight line near 10^{22} Hz is the estimate of a galactic component that was provided by Fichtel et al. The large MeV bump proved to be an artifact (Sreekumar et al. 1998; see Weidenspointner (1999) for a detailed independent description of the *Comptel* data analysis that led to this important advance.)

$$= N\,1.9864 \times 10^{-9}\,\frac{ergs\;Hz^{-1}}{\nu} \cong \frac{N}{5\times 10^{8}}\frac{ergs\;Hz^{-1}}{\nu}$$

If N is independent of frequency (a flat spectrum) then

$$\int_{\nu'}^{b\nu'} N\;photons\;nm^{-1}d\nu = \int_{\nu'}^{b\nu'}\frac{Nhc}{\nu 10^{-7}}\;ergs\;Hz^{-1}d\nu = \frac{Nhc}{10^{-7}}\ln(b)\;ergs$$

This demonstrates that, whatever the frequency ν' from which we integrate, as long as we integrate over a specified factor *b* in frequency we will obtain the same amount of energy.

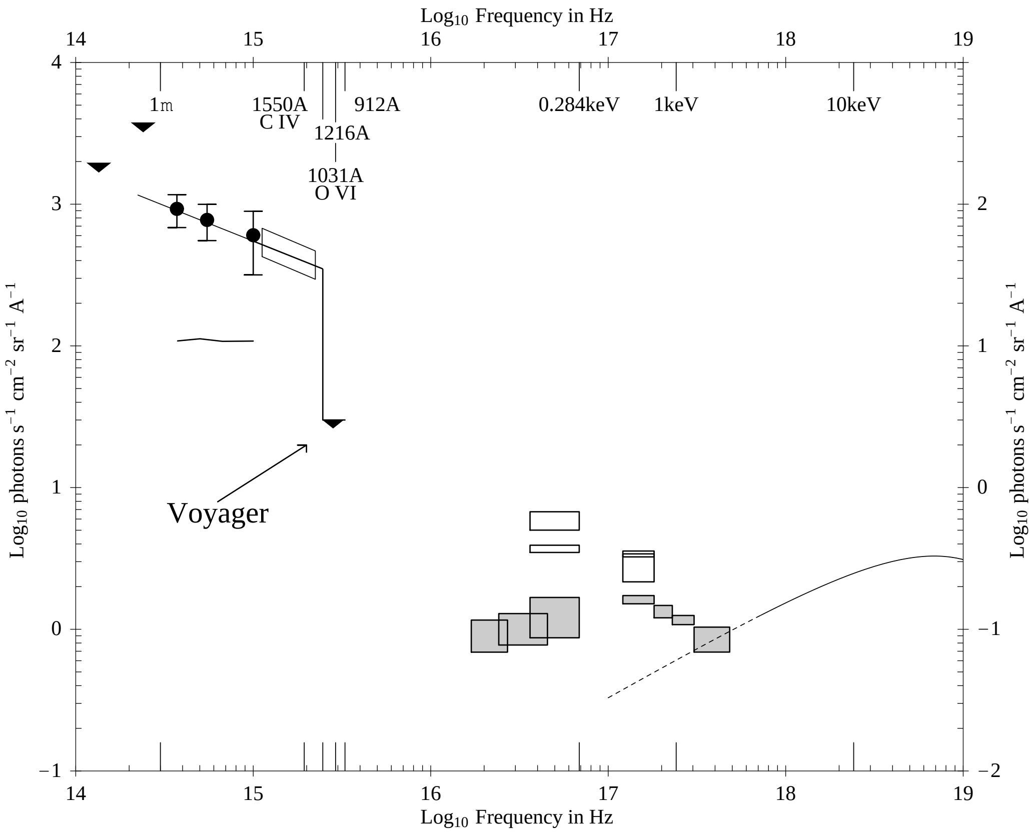

Fig. 2. The spectrum of the visible, ultraviolet, and soft X-ray portions of the diffuse background radiation. The wavelengths of two important interstellar medium emission lines, O VI 1031Å and C IV 1550 Å, are identified, and the Carbon edge at 0.284 keV is also identified.

Please note also, that although my work centers on diffuse radiation, the remarks about units apply equally to the spectra of point sources. The fact that the radiation is diffuse only affects the sr^{-1} portion of the units, which does not enter at all into the foregoing discussion.

2. Further Remarks on Units

In Henry (1999a) I pointed out the grossness of the exaggeration of the importance of the radio background that is caused by the use of units I_ν. It amounts to a factor of 10^{17} across the spectrum from radio waves to gamma rays. There is, however, a system of units that is even worse. It is units of *photons* s^{-1} cm^{-2} sr^{-1} MeV^{-1}. To flatten I_ν requires multiplication by the frequency (to produce νI_ν), or alternatively, division by the wavelength. To flatten "photons per MeV" requires division by the *square* of the wavelength, and so use of such units suppresses the apparent importance of the gamma-ray background by a factor of 10^{34} compared with the radio background! Remarkably, these units were used, not by radio astronomers, but by gamma-ray astronomers. More recent efforts by gamma-ray astronomers center on use of units E^2 dJ/dE $(keV^2/(cm^2\text{-}s\text{-}keV\text{-}sr)$ which are indeed flat. Again, I strongly recommend, instead, *photons* s^{-1} cm^{-2} sr^{-1} nm^{-1}, which are both flat and natural.

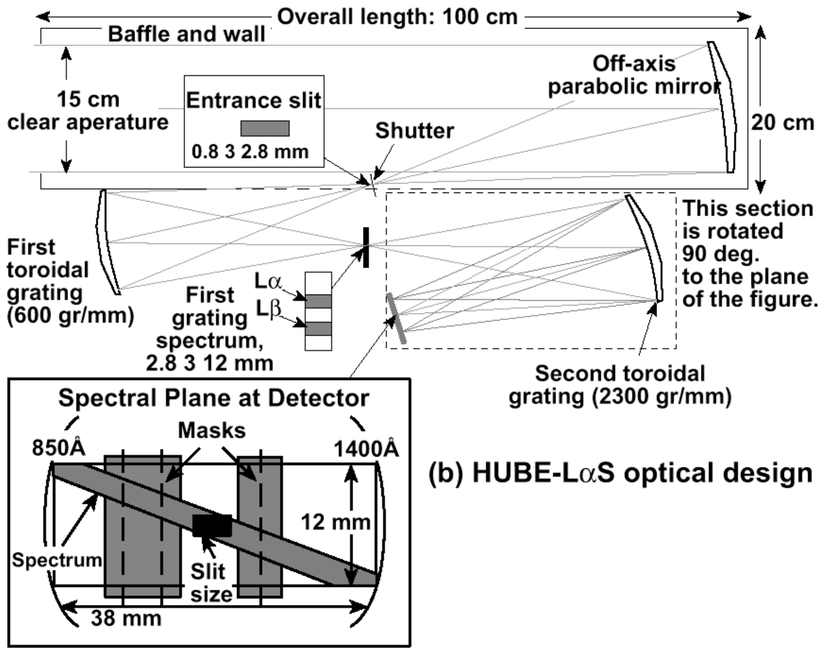

Fig. 3. Dr. Keith Peacock's design for the HUBE Lyman α Spectrometer, LαS.

3. How to Plot the Spectrum of a Black Body

In Figure 1, I show the background radiation spectrum of the universe. The most prominent single feature is, of course, the famous 3*K* background radiation. This microwave background is shown for a temperature of 2.714K (Fixsen et al. 1994). I now spell out in detail the method for plotting of a black body spectrum. From the bottom of page 104 of Allen (1973),

$$N_\lambda = \frac{2\pi c}{\lambda^4}\frac{1}{e^{\frac{w}{\lambda T}}-1}\frac{photons\ cm^{-2}s^{-1}}{cm} = N_\lambda \frac{photons\ s^{-1}}{cm} from\ a\ 1\ cm^2\ area\ dA,$$

where w = 1.43883 *cm K*. However, this is radiation *from or onto a flat surface*. In any given direction (θ, φ) the dA cm^2 area will appear foreshortened to dA $\cos\theta\ cm^2$. Integrated over the outward hemisphere, we have

$$\int dA\cos\theta\ d\Omega = \int_0^{2\pi}\int_0^{\frac{\pi}{2}} dA\cos\theta \times \sin\theta\ d\theta\ d\varphi\ cm^2 sr = dA\ \pi\ cm^2 sr = \pi\ cm^2 sr$$

So we have finally,

$$\frac{2\pi c}{\lambda^4}\frac{1}{e^{\frac{w}{\lambda T}}-1}\frac{photons\ s^{-1}}{cm}\frac{1}{\pi\ cm^2 sr} = \frac{2c}{\lambda^4}\frac{1}{e^{\frac{w}{\lambda T}}-1}\frac{photons\ cm^{-2}s^{-1}sr^{-1}}{10^7 nm}$$

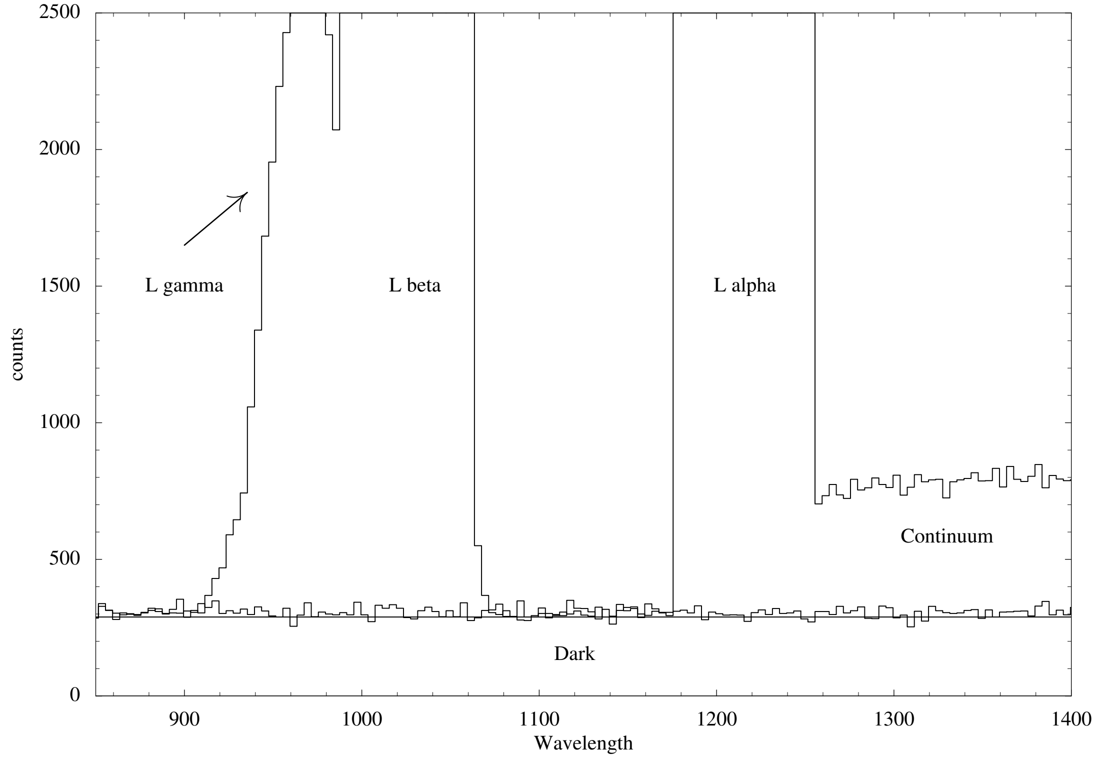

Fig. 4. Simulated data from an observation with HUBE Lyman α Spectrometer, LαS. The spectrum displays counts per Ångstrom against wavelength in Ångstroms

That the above result is worth specifying in the detail I have given, is shown by the fact that at least twice in the pages of the august *Annual Reviews of Astronomy and Astrophysics* the black body spectrum is plotted incorrectly (Henry 1991; Fabian and Barcons 1992).

4. The Visible, Ultraviolet, and Soft X-ray Background

In Figure 2, I provide a greatly magnified view of the visible, ultraviolet, and X-ray portions of the diffuse background radiation. Compare with Figure 1 - in Figure 2, I omit the interstellar photoionization cross-section, and also, instead of the Burrows *simulation*, I provide the soft X-ray *observations*. The seven lower shaded boxes are from the review of McCammon and Sanders (1990). The upper boxes are the earliest soft X-ray background observations, identified individually in Henry (1999a). Another version of this same figure appears in Henry (1999b); that version includes *both* the Burrows simulation *and* the boxes, for comparison purposes.

5. The Break in the Ultraviolet Background at 1216 Å

In Figures 1 and 2, and in Henry (1999a), I call particular attention to the very substantial break in the diffuse ultraviolet background spectrum that occurs near (indeed, I suspect *at*) 1216 Å. As part of my unsuccessful 1998 MIDEX re-proposal of HUBE (Hot Universe Background Explorer) I included a new instrument, which I call Lyman Alpha Spectrometer (LαS) which was designed for me by Dr. Keith Peacock of the Johns Hopkins University's Applied Physics Laboratory. The concept of such an instrument, capable of observing across the strong solar-system and geocoronal Lyman α emission, was suggested to me by Professor William G. Fastie. The instrument achieves our aim by cross-dispersing the light, so that the Lyman α falls off of the measured spectrum. The only Lyman α that can be fouling our spectrum is that which is doubly scattered. I quote Dr. Peacock's description of the design (see Figure 3), from my HUBE proposal:

"The Straddle spectrometer will map the distribution of the diffuse ultraviolet radiation background over the spectral range 850 Å to 1400 Å with a spectral resolution of 40 Å. This spectral range is chosen to straddle the wavelength (1216 Å) of the Lyman-α line, and employs a cross dispersion design to minimize scattering from local Lα radiation. In the double-pass spectrometer the first stage of dispersion uses masks to eliminate direct Lα, Lβ, and Lγ. The second stage of dispersion, at right angles to the first, will concentrate the scattered Lyman lines onto a small masked area of the detector. Thus, only light that is scattered twice will be present to contaminate the diffuse background spectrum. Since our holographic gratings scatter at a level much better than 5×10^{-5} Å^{-1}, the result is completely negligible contamination at a level of less than 25×10^{-10} Å^{-1}.

The diffuse background has never before been measured with a double-pass spectrometer, which is the only way of making an unimpeachable measurement in the presence of the ubiquitous and intense geocoronal Lα radiation. A baffled off-axis parabolic mirror, aperture 15 cm and focal length 40 cm, collects and images the incident energy onto a field stop. The field stop size, 2.8 by 0.8 mm, sets the FOV at 0.4° by 0.11° and the spectral resolution at 40 Å. Energy from the stop falls onto the first toroidal diffraction grating (radius of curvature of 300 mm) in the first Rowland circle spectrograph. Its 600 lines/mm ruling disperses the spectral range 850-1400 Å across a 12 by 2.8 mm aperture. This aperture has masked portions with widths of 1.0 mm (20 % larger than the slit image) to eliminate the directly imaged Lyman lines. The full spectrum is still overlaid by scattered Lyman radiation. The second Rowland spectrograph (radius of curvature also 300 mm) orients its grating perpendicular to that of the first and uses 2300 lines/mm to disperse the 850 to 1400 Å spectrum across 38 mm of the detector. The major advantage of using this arrangement is that the overlying stray hydrogen lines are imaged into limited masked areas of the detector as shown in Figure 12. Any remaining Lα, has to have been scattered by both gratings. The inset shows the distribution of energy across the detector focal plane. The instrument has been fully ray-traced and has rms spot radii of 0.14-0.3 mm. Thus the resolution is limited by the size of the field stop and not by the aberrations. The detector uses a KBr photocathode to provide high efficiency throughout the far UV and its cutoff at ~1600 Å protects the spectrograph from scattered light at longer wavelengths (red leak). To maximize the optical efficiency over the full spectral range the optics will be coated with ion-beam sputtered silicon carbide, SiC. Direct JHU experience with these coatings has been obtained in the Hopkins Ultraviolet Telescope (HUT), Sounding Rocket, and Lyman FUSE programs. Reflectances of 30% at 850 Å, rising steadily to 40% at 1400 Å have been achieved. In other JHU programs absolute grating efficiencies of 22-27% have been achieved. In this analysis grating efficiencies of 15% and mirror reflectances of 35% have been used in the performance analysis. The total optical efficiency for two gratings and a mirror is 0.8%. The lower optical efficiency and the smaller aperture (150 mm vs. 180 mm) in comparison with the FUVS are compensated by the wider spectral resolution, 40 Å versus 5 Å, making the two instruments comparable in sensitivity."

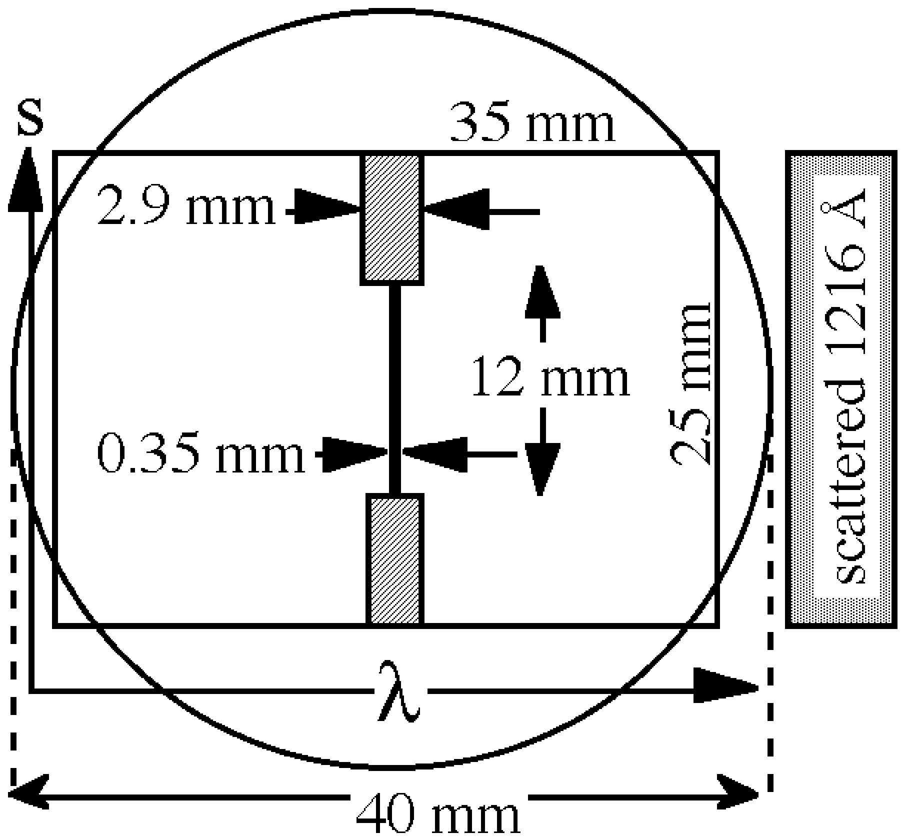

Fig. 5. Slit design for the HUBE Extreme Ultraviolet Spectrometer, EUVE. The slit is narrowest where the detector has its best spatial resolution, and is wider toward both edges of the detector to allow greater throughput for detection of the faint cosmic background continuum.

6. Simulated Data from the Lyman Alpha Spectrometer

In Figure 4 I show my simulation of the data that we might hope to obtain through use of the Lyman Alpha Spectrometer, LαS. The simulation shown is for the cheerful case that my suspicions concerning the spectrum of the cosmic diffuse ultraviolet background break at 1216 Å are correct. Extremely strong geocoronal/solar-system Lyman α,β, and γ appear in the simulation, but shortward of Lyman α only dark-current appears. In practice the strong local features would not be present, suppressed as described in the previous section. If my ideas concerning the break should turn out *not* to be correct, the continuum would continue down to, but not beyond, the interstellar photoionization edge at 912 Å.

7. Measuring O VI and the Continuum Simultaneously

Finally, I describe another nice feature of HUBE, the clever design (Figure 5) for the slit of the Extreme Ultraviolet Spectrometer, EUVS, which features a narrow-slit region near the center of the detector, where the resolution of the microchannel plate detector is best. The width of slit there has been carefully chosen to allow us to resolve the very important astrophysical line O VI from the terrestrial Lyman β. But the two outer portions of the slit are much wider, to allow detection with good signal-to-noise of the diffuse background continuum against which we expect the O VI line to be seen.

8. Conclusion

Most astronomers have interests that center on study of radiation from point sources. Diffuse cosmic background radiation has typically entered astronomy either by accident, or through the efforts of physicists. The discovery of the 3K background (which led to a Nobel Prize) was accidental; the ability of IRAS to measure diffuse backgrounds, in addition to point sources, was an unexpected byproduct of the mission. With HUBE, I aim for *deliberate* exploration of a new frontier; a frontier that I believe holds great promise for astronomical discovery.

Acknowledgements

I am grateful to the Center for Astrophysical Sciences for support.

References

Allen, C. W.: 1973, *Astrophysical Quantities*, Athlone Press.
Bernstein, R. A.: 1998, *PhD Thesis*, California Institute of Technology.
Burrows, D.: 1996, The CUBIC Handbook, (publication available from http://www.astro.psu.edu/xray/cubic/papers/handbook/).
Fabian, A. C., and Barcons, X.: 1992, *Ann. Rev. Astron. Astrophys.* **30**, 429.
Fichtel, C. D., Simpson, G. A., & Thompson, D. J.: 1978, *Astrophys. J.* **222**, 833.
Fixsen, D. J. et al.: 1994, *Astrophys. J.* **420**, 445.
Fixsen, D. J., Dwek, E., Mather, J. C., Bennett, C. L., & Shafer, R. A.: 1998, *Astrophys. J.* **508**, 123.
Hauser, M. G., Arendt, R. G., Kelsall, T., Dwek, E., Odegard, N., Weiland, J. L., Freudenreich, H. T., Reach, W. T., Silverberg, R. F., Moselely, S. H., Pei, Y. C., Lubin, P., Mather, J. C., Shafer, R. A., Smoot, G. F., Weiss, R., Wilkinson, D. T., and Wright, W. L.: 1998, *Astrophys. J.* **508**, 25.
Henry, R. C.: 1991, *Ann. Rev. Astron. Astrophys* **29**, 89.
Henry, R. C.: 1999a, *Astrophys. J. Lett.* **516**, 49.
Henry, R. C.: 1999b, *The Low Surface Brightness Universe*, IAU Colloquium No. 171, ASP Conference Series **170**, ed. J. I. Davies, C. Impey, & S. Phillips, 357.
McCammon, D., & Sanders, W. T.: 1990, *Ann. Rev. Astron. Astrophys* **28**, 657.
Murthy, J., Hall, D., Earl, M., Henry, R. C., & Holberg, J. B.: 1999, *Astrophys. J.,* in press.
Sreekkumar, P., et al.: 1998, *Nature* **391**, 866.
Weidenspointner, G.: 1999, *The Origin of the Cosmic Gamma-Ray Background in the Comptel Energy Range*, Dissertation, Max-Planck-Institut für extraterrestrische Physik, Garching.