The Intergalactic Medium

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Abstract. It is remarkable that a small space satellite mission can be created that has, potentially, the capability of detection of the dark matter of the universe, and in particular, detection of the intergalactic medium. I describe the approach for such a sample mission, and I also briefly comment on, and *illustrate*, black holes; black holes represent another candidate for the "missing" baryonic dark matter in the Universe.

INTRODUCTION

I ask the question, what role can small missions (say, NASA SMEX and MIDEX missions) play in the search for the intergalactic medium and the search for the dark matter of the Universe. I am the Principal Investigator on HUBE (which currently stands for "*Hot Universe Background Explorer*.") HUBE is an example of a mission that one could hope might lead to the direct detection of the intergalactic medium. The high point (so far) in my attempt to implement HUBE, was the acceptance of HUBE by NASA in 1996 as the MIDEX alternate to MAP. HUBE will be submitted once again in the next SMEX round, and of course I very much hope for actual implementation.

THE HUBE MISSION

It is widely agreed that even if the Universe is open, with a small non-zero cosmological constant, there is a very large amount of dark matter in the Universe. As much as 90% of the baryonic dark matter has yet to be detected, and the non-baryonic dark matter, which could make up as much as 90% of the total matter in the Universe, is entirely undetected. This is a very fat target indeed, but one that seems to be very difficult to hit.

While HUBE has many astrophysical goals beyond the hope of detection of the intergalactic medium (please see my paper on the interstellar medium at the present workshop), the search for the dark matter of the Universe is my core reason for the creation of HUBE. The HUBE mission is aimed at spectroscopy of the diffuse ultraviolet background radiation. The existing such observations are collected in Figure 1, which I have adapted and improved from Henry and Murthy (1994). I have kept the labeling of the observations the same as in Henry and Murthy (1994), so that references for the individual points can easily be found by consulting that publication. The main improvement in the figure (other than reversing it to have energy increase to the right) is the inclusion of the new and much lower Voyager (*V*) upper limit of Murthy et al. (1999) short of 1000 Å.

The reversal of the energy scale allows more convenient comparison of the detailed observations with those in the visible and in the soft X-ray part of the spectrum, which are laid out in Figure 2. Figure 2 also includes the entire regime of operation of HUBE, in spectral terms. The three solid filled points in Figure 2 are those of Bernstein (1998), representing the optical background radiation. The narrow line below her three points are her integration of the galaxies in the same field of view (HDF). A significant diffuse optical background is seen, that is of unknown origin. That this background is truly diffuse has been demonstrated by Vogeley (1998).

Of course the big excitement from the point of view of cosmology, is the large jump in the diffuse background that occurs at (or near) Lyman α. On the face of it, a diffuse background that shows this behavior is begging to be interpreted as being made up of redshifted Lyman α radiation from the missing baryonic dark matter, which would in these circumstances be made up of intergalactic clouds of the type that are discussed by R. Cen at this workshop.

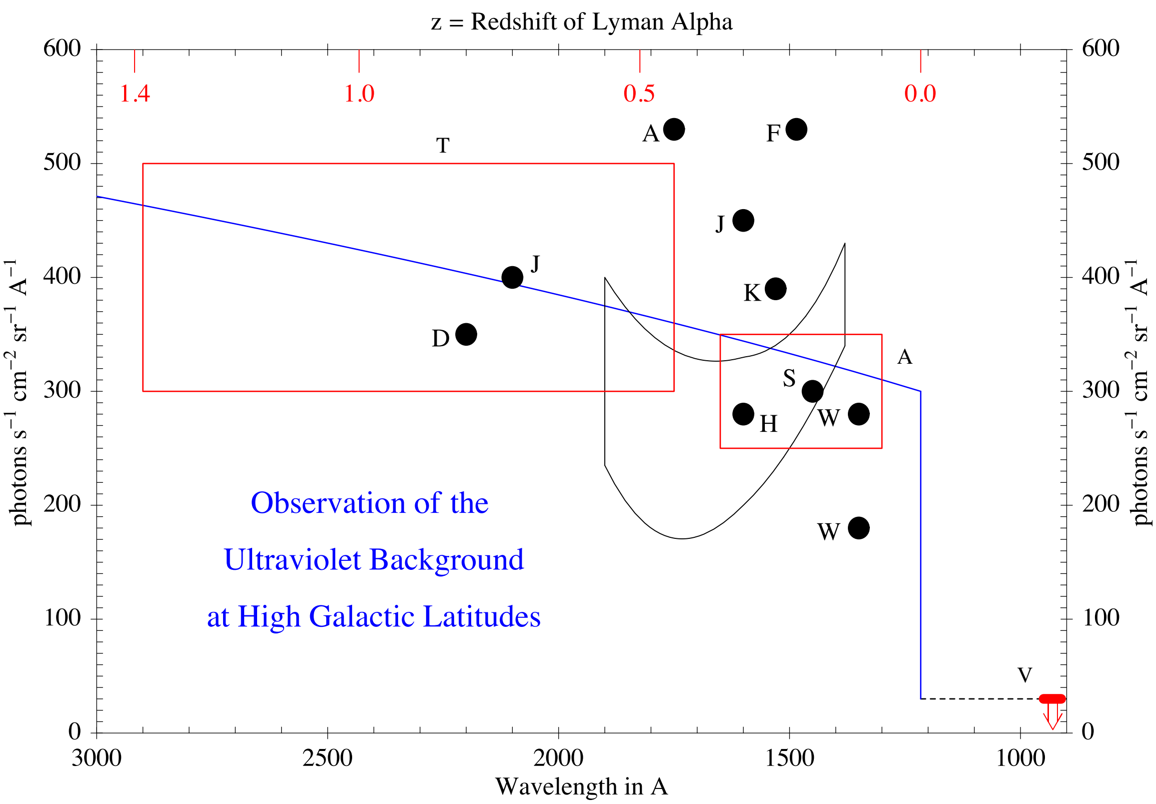

FIGURE 1. Existing Observations of the Diffuse Cosmic Background Radiation. References to individual observations may be found in Henry and Murthy (1994). The most interesting data point is the Voyager upper limit of Murthy et al. (1999), marked with a *V*. The thin solid line shows a model of the emission expected from clumped clouds of intergalactic gas that expand as the Universe itself expands. The solid points are all actual detections of diffuse radiation, and the spread in values reflects real point-to-point variations in the brightness of the background radiation. In contrast, the Voyager observation is simply an upper limit.

The problem with this interpretation is that, while it is easy to obtain the observed intensity of radiation by clumping the gas to a reasonable degree, an additional result of the clumping is that the recombination time becomes shorter than a Hubble time, and some unknown source of ionization is required to keep the intergalactic medium transparent as it is observed to be. I have suggested (Henry 1999) that the putative neutrinos of Sciama (1997) would do the job, but of course I am not averse to any source: *but* the ionizing radiation, *I do need!*

The observations that are given in Figures 1 and 2 were made at high galactic latitudes. The environment (in the ultraviolet) for such observations at high *southern* galactic latitudes is shown in Figure 3. The shading is integrated ultraviolet (1565 Å) radiation from stars. The coordinate system is ecliptic, which is the coordinates of the "worst noise" from the point of view of the *optical* background. Note that the coordinate labels refer to ecliptic coordinates, not to the superimposed galactic coordinates. The interference by direct starlight is not serious at high galactic latitudes, the stars being few and faint. However, the potential for high-galactic-latitude dust back-scattering of ultraviolet starlight is very real, and provides

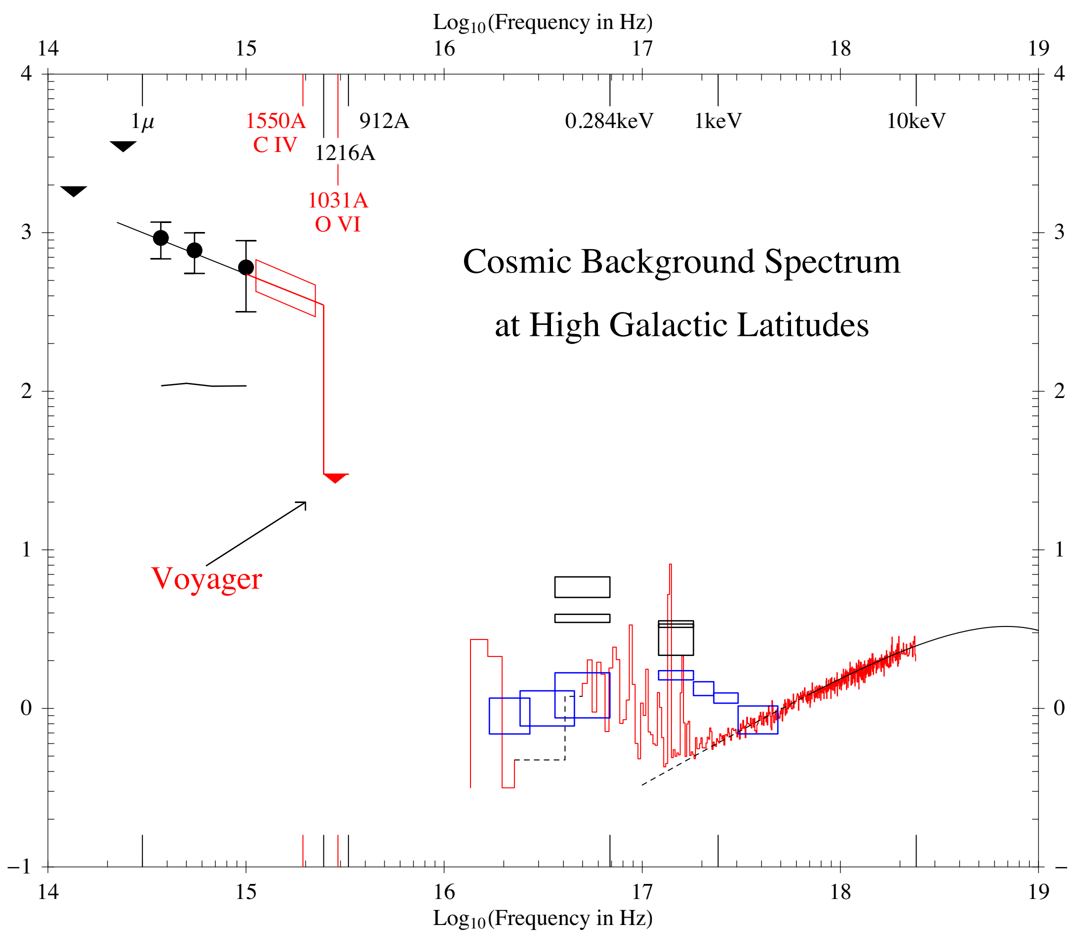

FIGURE 2. The Diffuse Background, from the Visible to X-ray Energies. In this figure, the Voyager and other ultraviolet observations from Figure 1 are shown adjacent to the visible background radiation observations of Bernstein (solid dots). References to other observations in this figure may be found in Henry (1999). The detailed X-ray spectrum is a simulation, due to David Burrows, of what CUBIC (Burrows 1996) could accomplish, if implemented as part of the HUBE project.

the only realistic alternative to my cosmological interpretation of the observations (assuming that the observations are correct!). That alternate interpretation is, of course, that we are seeing starlight back-scattered from dust.

There are two answers to this, the first being simply that it would be remarkable indeed if the scattering properties of interstellar dust were such that a break in the magnitude of the scattered signal as large as that shown in Figures 1 and 2 should occur at all, much less that it should fortuitously occur near the wavelength of Lyman α. The second argument is perhaps better, and that is, that Murthy et al. (1994) have observed the Coalsack Nebula using the Voyager ultraviolet spectrometers (both Voyager *1* and Voyager *2*), and do *not* see any such break in the spectrum of what is clearly dust-scattered starlight.

A sample of diffuse ultraviolet background radiation is given in Figure 4. This is the spectrum of a high-latitude target observed with the UVX experiment on the Space Shuttle (Murthy et al. 1989, 1990). What is shown in a scan over a few degrees, spectrally resolved from Lyman α (1216 Å) to 3000 Å. Even though a Calcium Fluoride filter is present to attenuate Lyman α, a strong solar-system Lyman α line is seen. This gives an accurate impression of how difficult it is to observe *shortward* of Lyman α, where that emission must be admitted to the spectrometer.

Toward the end of the scan shown in Figure 4 (upper part of the figure), strong terrestrial emission is seen. Throughout the scan, weak terrestrial OI emission at 1304 Å and 1306 Å is also seen. A few horizontal lines are the spectra of stars passing through the field of view. Vertical bands of emission in the right half of the figure are zodiacal light, which declines sharply in intensity in the HUBE spectral region, that is to say, below 2000 Å.

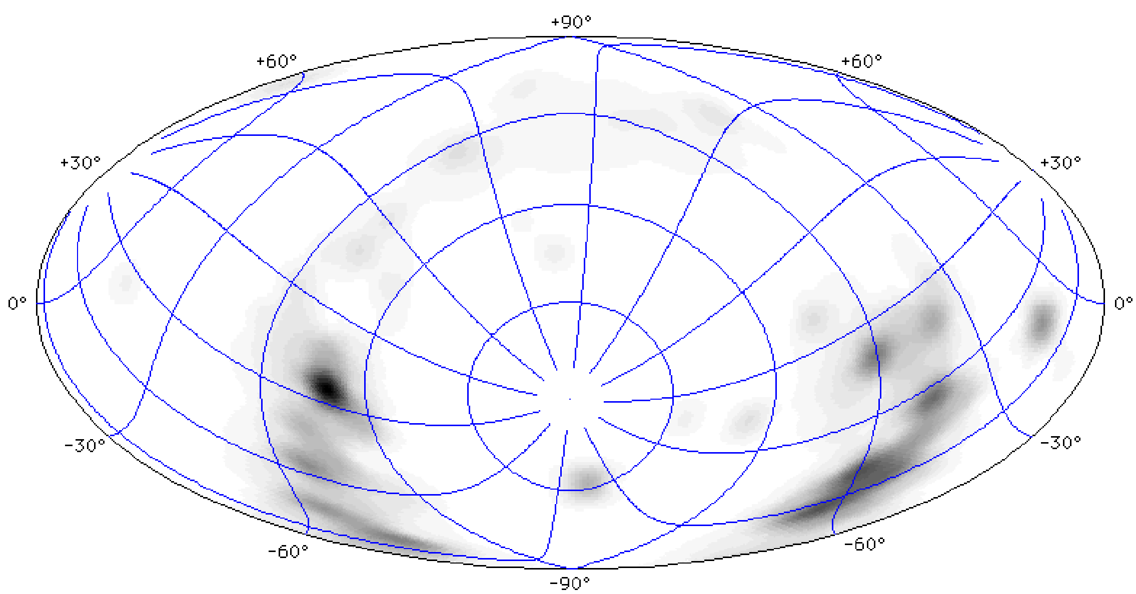

FIGURE 3. The Celestial Sphere in Ecliptic Coordinates (Galactic Coordinates superimposed). The shaded background is the integrated light of stars in the ultraviolet. Zodiacal light is symmetric with respect to ecliptic coordinates, but does not show as much variation with ecliptic latitude in the ultraviolet as it does in the visible (Murthy et al. 1990).

To observationally explore a baryonic intergalactic medium consisting of hot gas clouds in the temperature range 10^5-10^6 K requires spectrometers spanning the ultraviolet and soft X-ray spectral regions, and that is precisely what HUBE offers (see the X-ray HUBE simulation in Figure 2). What could HUBE teach us about background radiation and the intergalactic medium? If, in the ultraviolet, as is strongly suspected (e.g., Witt and Petersohn 1994), there is an extragalactic component to the background radiation, we would, with HUBE-FUVS continuum measurements (and guided by HUBE-L αS and HUBE-EUVS [these acronyms are identified, and the corresponding instruments characterized, in my paper on the interstellar medium in the present volume] step-size measurements), create a three-dimensional map of emission from the nearby ionized intergalactic medium. Simultaneously, with HUBE-CUBIC, we would make the definitive measurements of the Cosmic X-ray Background Radiation (CXRB) spectrum, in a search to understand its origin. All previous CXRB mappings (Wisconsin rockets, SAS-3, HEAO-1, and ROSAT) used proportional counters, which have very poor energy resolution. In only six months' exposure, HUBE-CUBIC would measure the spectrum of the CXRB with larger total exposure than HEAO-1 but with an eight-fold improvement in spectral resolution. (Sensitivity to diffuse emission depends on the instrument *étendue*, AΩ: HUBE-CUBIC is significantly more sensitive than any previous mission other than HEAO-1.) Our excellent spectral resolution combined with high sensitivity would be vital for understanding the origin of the CXRB: it is believed (Ueda et al. 1998) that most of the flux in the 1-2 keV band comes from weak sources at high *z*, primarily AGN's. Iron K-line emission from AGN sources should produce structure in

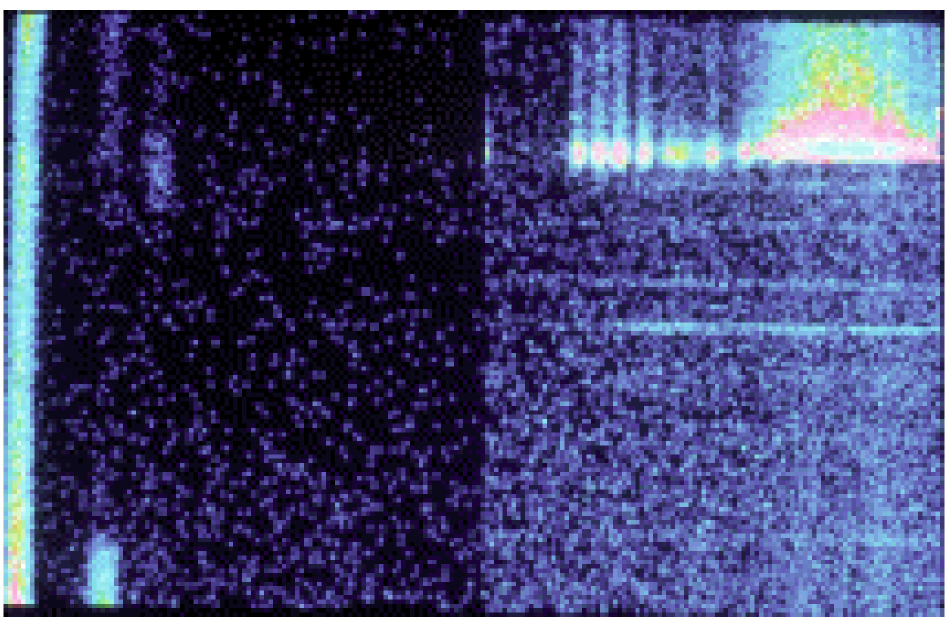

FIGURE 4. An observation of the diffuse ultraviolet background. Various terrestrial features are describe in the text. The sharp break in the background that occurs about half way across the figure, is due to different instrumental backgrounds in the two scanning spectrometers employed aboard the Space Shuttle in making the observations. Control of instrumental background is a key priority of the HUBE mission.

the CRXB spectrum strongly indicative of their evolution (Boldt 1987; Schwartz 1990; Matt and Fabian 1994; Gendreau 1995). For high redshifts ($1 < z < 5$), this structure would appear in the 1-3 keV band, a regime that is complicated in imaging instruments by M-shell spectral distortions from the gold coating used in grazing incidence X-ray telescopes. Being devoid of such complications, HUBE-CUBIC is an ideal instrument for carefully examining CXRB spectral signatures of iron K-line emission by high redshift extragalactic sources. Such measurements require long exposures averaging over large solid angles to measure deviations of a few percent from the CXRB continuum. This is a challenging observation, but one with rich scientific rewards: direct measurement of AGN evolution from their composite spectrum.

Now let me turn to another topic, black holes, which are regarded in some quarters as a candidate "hiding place" for at least some of the missing baryonic dark matter. However, I will discuss the *physics* of black holes, rather than their potential significance as dark-matter candidate.

BLACK HOLES

Observational astronomers are often nonplussed when General Relativists assert that we can learn no black hole physics from observations of black holes. The General Relativists are correct, however, and the reason is both simple and profound. Black holes are *deeply* understood. Let me demonstrate how simple they are by deriving their existence, assuming that the reader already knows about tensors. Even if the reader does *not* know about tensors (simple enough mathematics!) my point, which is the utter simplicity of black holes, should be proven to the reader's satisfaction. Tensors are sets of functions of the coordinates that are in a sense coordinate-independent and hence are suitable for expressing laws of physics. One simple but very important example of a tensor is *0*, which is certainly independent of coordinates! The set of functions $g_{\mu\nu}$ describes a geometry, and is called the metric tensor. The subscripts μ and ν go from one to four, because the Universe has three space dimensions and one time dimension, which totals four. Einstein's fundamental idea was that geometry (our set of functions) is equal to mass-energy, which is zero outside a star: for example, anywhere in the solar system. So, one's first guess at the law of gravitation would be $g_{\mu\nu} = 0$. However, that is clearly no geometry at all. Thus, if one is driven to pursue Einstein's idea, it is necessary to find the next most complicated tensor that involves only the metric tensor. It takes only a page of effort to find $R^{\alpha}{}_{\beta\gamma\delta}$, and one's next guess clearly would be to set this *new* tensor equal to zero. However, our new tensor is a very famous tensor, the Riemann tensor, and when it is zero, the spacetime involved is defined to be flat. (That, of course, is because it *is* flat for spaces and spacetimes we normally consider to be flat.) So, our second guess is a dismal failure. However, it is possible to form a lower-order (i.e., fewer indices) tensor from any tensor by a purely mathematical process called contraction, which involves setting a raised and lowered index equal to each other and summing, to form a new set of (fewer) functions. For example, let us contract the Riemann tensor: $\Sigma\ R^{\alpha}{}_{\beta\alpha\delta}, = R_{\beta\delta}$. Our third try, of course, is $R_{\alpha\beta} = 0$, ... which are the vacuum field equations of General Relativity. Trivial!

Einstein felt that these equations were too complex to ever allow an analytic solution, but he was very wrong: within six months, the father of my friend the late Martin Schwarzchild found the famous Schwarzschild solution:

$$ds^2 = \frac{1}{1-\dfrac{2m}{r}}\,dr^2 + r^2 d\theta^2 + r^2\sin^2\theta\, d\varphi^2 - \left(1-\frac{2m}{r}\right)dt^2$$

This is one of the most astounding equations in all of physics. The coefficients of the squared coordinate differentials are the four non-zero components of the metric tensor. Schwarzschild's metric differs from the metric of plain ordinary flat spacetime only in the presence of the parameter m, which is the mass of the sun (about a kilometer in appropriate units). This equation predicts Newtonian gravitation as its first approximation, and predicts the precession of the perihelion of Mercury (which was previously unexplained) and also predicts (and *this* prediction you can *see*) the possibility of black holes: you will notice that if distance from the central mass m is $r < 2m$, the negative sign of the final term (time) changes from negative (which is what identified it as *being* time) to positive, while at that same distance the first term, which had been distance from the sun, becomes negative. The two coordinates switch roles! You cannot go back, because you cannot go back in time.

There is nothing more to it than that!

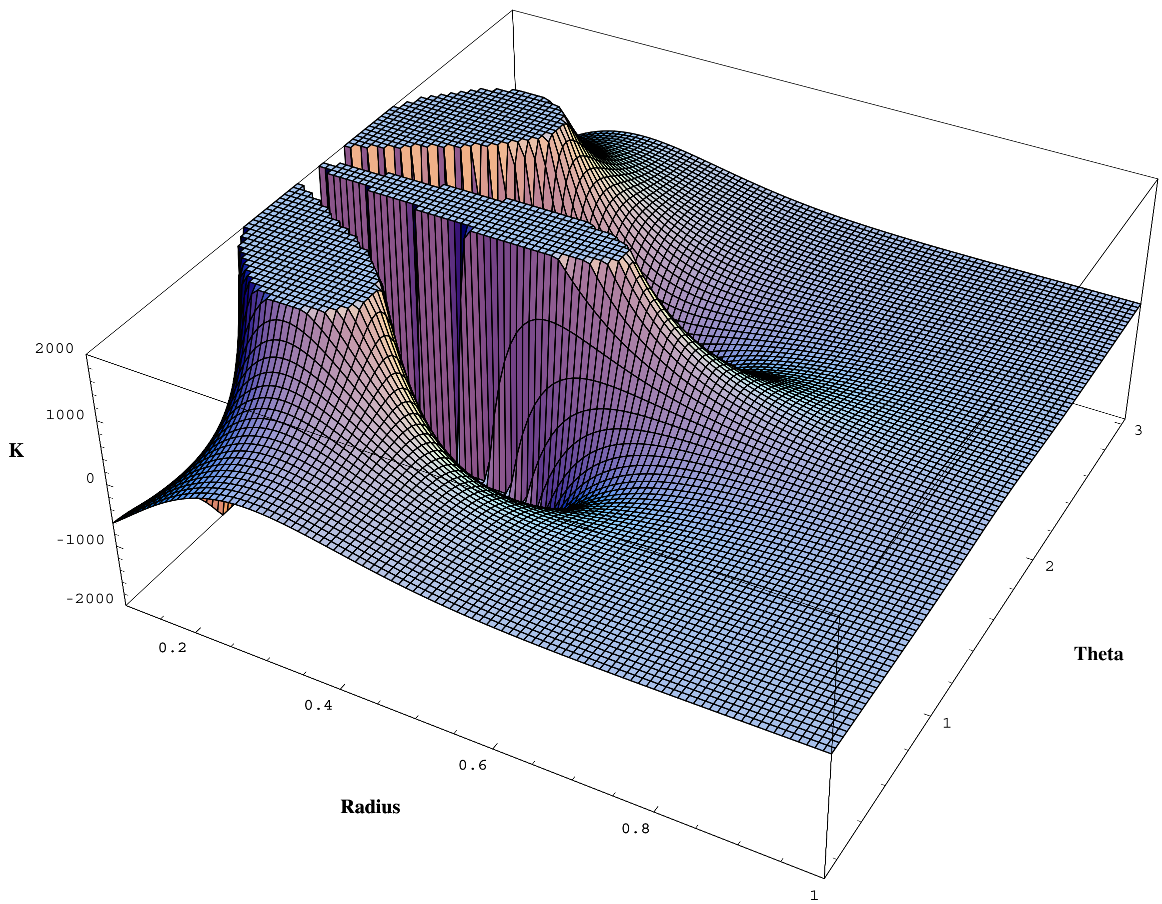

FIGURE 5.—A conceptual photograph of a black hole, showing how curved the black hole is as a function of distance from the black hole ("Radius") and North Polar Angle ("Theta"). This particular plot is for a value of a = 0.6 (angular momentum per unit mass) and for electric charge Q = 0.2. Real black holes in the Universe are unlikely to be electrically charged.

Real black holes in the Universe (black holes that might make up the baryonic dark matter) are, however, not Schwarzschild black holes. They are surely Kerr black holes, which have the added attribute of angular momentum (and, in principle, also electric charge, although real black holes would easily electrically neutralize by strongly attracting the needed charged particles from their environment.)

A picture of a general black hole is shown in Figure 5. What is plotted is the curvature of spacetime, as a function of distance ("Radius") from the rotating and electrically-charged black hole, and of north-polar distance ("Theta"). The quantity plotted is the Kretschmann scalar K, about which a word is necessary.

If we perform our operation of contraction on $R_{\alpha\beta}$ (after, of course, raising one index) we get $R^{\alpha}{}_{\alpha} = R = 0$, where the final step follows from the vacuum field equations. The gaussian curvature R of spacetime around a black hole is zero! That is in contrast to, for example, a beachball, which has gaussian curvature $2/a^2$,where a is the radius of curvature of the beachball. However, there is *another* scalar which can be formed from (multiple) contraction of the Riemann tensor: $K = R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}$, and K is non-zero for a beachball ($4/a^4$) *and* is also non-zero for black holes. In Figure 1 you are *really* seeing a black hole, in just as intellectually-meaningful a sense as you have ever seen a beachball.

I have never seen a plot of K in any book on General Relativity, and also, I have never seen the algebraic expression for it published, so: I publish it here:

$$
\begin{aligned}
K = \frac{m^2/2}{(r^2 + a^2\cos 2\theta)^6}\Big[& -30a^6 + 540a^4r^2 - 720a^2r^4 + 96r^6 \\
& +45a^2\cos 2\theta\left(16a^2r^2 - 16r^4 - a^4\right) + 18a^4\cos 4\theta\left(10r^2 - a^2\right) - 3a^6\cos 6\theta \\
& -\frac{Q^2 r}{m}\left(360a^4 - 960a^2r^2 + 192r^4 + a^2\cos 2\theta\left(480a^2 - 960r^2\right) + 120a^4\cos 4\theta\right) \\
& +\frac{Q^4}{m^2}\left(42a^4 - 272a^2r^2 + 112r^4 + a^2\cos 2\theta\left(56a^2 - 272r^2\right) + 14a^2\cos 4\theta\right)\Big]
\end{aligned}
$$

I do not present the Kerr metric itself, because it is not pretty (for a relatively clean version of the Kerr metric, see Enderlein 1997).

How does it happen that an observational astronomer can be publishing these properties of black holes? The answer is, the miracle of computers. While Mathematica does not "do" tensors normally, I wrote a Fortran program to generate a script that Mathematica could execute. It generates the above equation in about half an hour on my Macintosh G3 Powerbook. We are rapidly entering a new world, where advanced mathematics will be in the hands of "οι πολλοι"

CONCLUSION

Revolutions are occurring in instrumentation, and in computer manipulation of mathematics and of data. One of the great unsolved mysteries of the Universe is that of dark matter and the intergalactic medium. I have shown how accessible the advanced mathematics of black holes has become, through the advent of powerful handy computers, and I have shown how a quite simple NASA mission could, perhaps, solve the mystery of the dark matter and the intergalactic medium.

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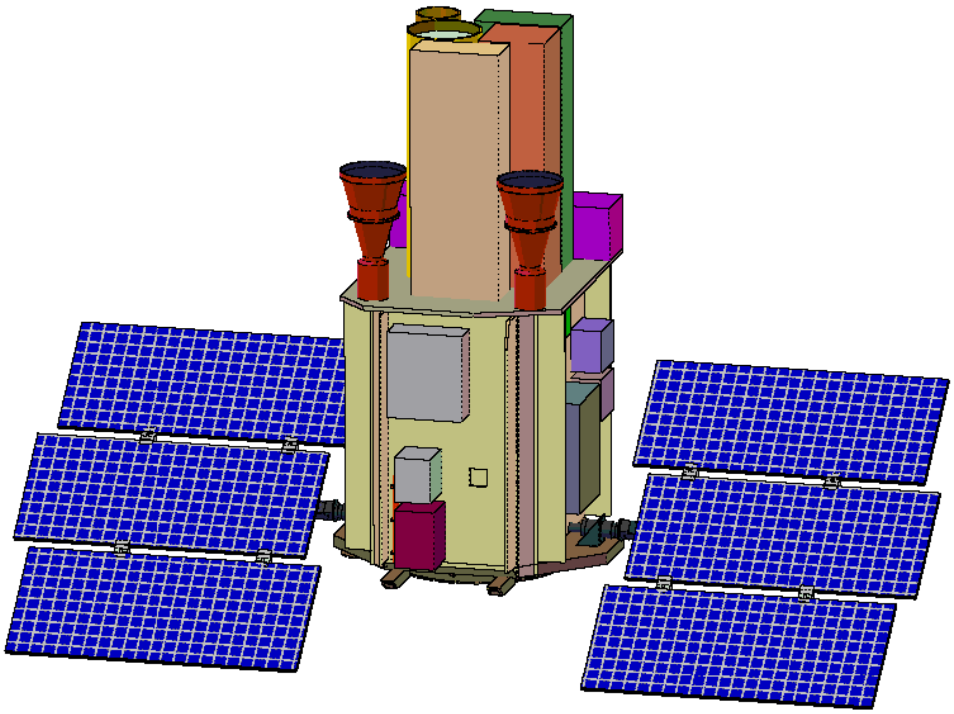

FIGURE 6.—The HUBE Instruments mounted in a Ball Aerospace RS2000 spacecraft. The instruments could be used to carry out a thorough all-sky spectroscopic survey of the X-ray and ultraviolet background radiation in about two years. This figure was provided by Mark Skinner.