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ULTRAVIOLET DETECTION OF VERY LOW-SURFACE-BRIGHTNESS OBJECTS

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ABSTRACT

The night-sky surface brightness at excellent ground-based sites is compared to the sky background in space. In directions typical of extragalactic pointings, the background in the space ultraviolet reaches μ_λ (2000 Å) = 26 mag arcsec^{-2}, which is a factor of 40 darker than at any wavelength on the ground. This represents an important new "window" for the study of extragalactic systems with low surface brightnesses. Taking into account the UV/V energy distributions of potential targets, we find that in certain favorable circumstances UV photometry may permit the detection of regions with equivalent V band surface brightnesses as low as 35 mag arcsec^{-2}, or over 100 000 times fainter than the ground-based night sky. We consider applications of UV surface photometry to the study of circumgalactic regions, dwarf galaxies, low-surface-brightness spirals, and the detection of primeval galaxies, and briefly discuss the usefulness of existing space instrumentation for such problems.

I. INTRODUCTION

The brightness of the night sky is a limiting factor in the signal-to-noise ratio obtainable in many astronomical problems. It is particularly serious in extragalactic studies, where our fundamental concept of the nature of stellar systems may have been strongly biased by selection effects imposed by the night-sky background (Arp 1965; Disney 1976, 1980; Allen and Shu 1979). As Disney (1976) put it: "...galaxies are like icebergs and what is seen above the sky background may be no reliable measure of what lies underneath."

An opportunity to survey the universe at significantly reduced levels of sky background might therefore be expected to yield important new insights into the nature of the galaxies. The space ultraviolet offers just such an opportunity because the sky background there is much darker than at visible or infrared wavelengths. This fact is not widely appreciated, and the purpose of this paper is merely to point out the important advantages of this situation for certain classes of extragalactic problems.

The night-sky brightnesses at a good ground-based site and in space are plotted for the 1500–8000 Å region in Fig. 1. Details on the calculation of these energy distributions are given in Secs. II and III, respectively, and the results are compared in Sec. IV. Applications to several extragalactic problems are discussed in later sections, and it is pointed out that UV observations permit detection of regions with equivalent V band surface brightnesses as low as 35 mag arcsec^{-2} in certain favorable circumstances.

II. THE GROUND-BASED NIGHT-SKY BACKGROUND

Measurements of the V or B band night-sky brightness have been published for a number of excellent existing or potential observatory sites over the last two decades. These include Kitt Peak (Hoag *et al.* 1973), Palomar (Turnrose 1974), Sacramento Peak (Schneeberger *et al.* 1979), Mauna Kea (Morrison *et al.* 1973), and a number of other sites in California and Arizona surveyed by Walker (1970, 1973). These studies are in agreement that the darkest sites, for example, Junipero Serra on the central California coast (Walker 1973), yield sky surface brightnesses of $\mu(V) \sim 21.9$ mag arcsec^{-2} for zenith distances $\lesssim 30°$ on moonless nights.

Less information is available on the wavelength dependence of the night-sky emission. The most useful published spectral energy distributions are those obtained by Turnrose (1974) at Palomar. In order to construct Fig. 1, we have assumed that the relative energy distribution of the night-sky continuum (a mixture of airglow, zodiacal light, and scattered natural and artificial light) is that given by Turnrose's Table II but that the normalization at 5500 Å is $\mu(V) = 21.9$ mag arcsec^{-2}, as discussed above.

In Figs. 1 and 3, surface brightnesses are plotted in monochromatic magnitude units, $\mu_\lambda = -2.5 \log S_\lambda - 21.1$, where $[S_\lambda] = \text{erg s}^{-1}\text{ cm}^{-2}\text{ Å}^{-1}\text{ arcsec}^{-2}$, based on the absolute calibration of the magnitude system by Hayes and Latham (1975).

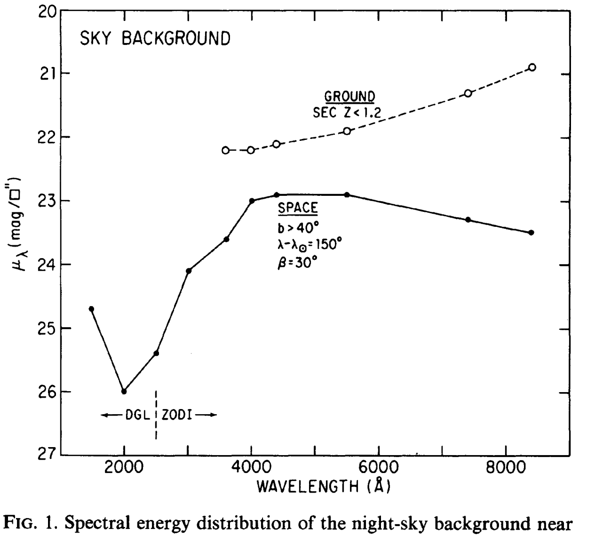

FIG. 1. Spectral energy distribution of the night-sky background near the zenith at an excellent ground-based site on a moonless night and in a direction typical of extragalactic pointings in space, estimated as described in Secs. II and III, respectively. The curves are plotted in monochromatic magnitude units (see Sec. II). The wavelength at which the diffuse galactic light (DGL) and zodiacal (ZODI) contributions to the space background are comparable for this pointing direction is indicated, and the arrows indicate the regions of dominance of one or the other. Effects of individual strong skyglow emission lines are not included, but the combined effect of OH emission bands on the ground is evident for $\lambda > 7000$ Å (see Fig. 2 and Sec. II).

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The contribution of individual strong airglow emission lines to the sky background has been removed from the data in Fig. 1. For the 3400–7000 Å region, natural airglow lines are not terribly intrusive, though city light pollution may be (see, for example, Osterbrock *et al.* 1976). Longward of 7000 Å, however, bright, blended OH emission bands dominate the night-sky background. It was not possible to remove the OH emission from Turnrose's spectra, which is evident in the rise in the ground-based energy distribution at the red end. The severity of the OH airglow at Kitt Peak may be judged from the higher-resolution spectrum shown in Fig. 2. The OH emission originates at an altitude of about 90 km (Roach and Gordon 1973) and will therefore not be a serious problem for the *Hubble Space Telescope* (*HST*) or other satellite observatories.

A final relevant point is that ground-based observations are subject to significantly higher backgrounds than plotted here about half the time at any site because of scattered moonlight. Scattering of moonlight by the residual atmosphere in space should be negligible, though excellent baffling is required to reject both moonlight and sunlight scattered from telescope or spacecraft structures.

III. THE SKY BACKGROUND IN SPACE

By the "night sky" background in space, we mean that prevailing in the Earth's shadow at low orbital altitudes ($\sim$200–800 km) or that prevailing in any direction $\gtrsim 60°$ away from the Sun at geosynchronous altitude ($\sim$40 000 km), where the *International Ultraviolet Explorer* now operates. The *HST*, *Spacelab* observatories, and most other missions carried to orbit by the Space Shuttle will operate at low altitudes, where airglow emission lines from the residual atmosphere produce a relatively bright and strongly variable sky background on the sunlit side (e.g., Cebula and Feldman 1984; Eastes *et al.* 1985). The only strong emission features in the night sky, however, are Lyα (λ 1216) and O I ($\lambda\lambda$ 1304,1356), which can be readily suppressed by suitable blocking filters if necessary for broadband observations in the 1300–2000 Å region.

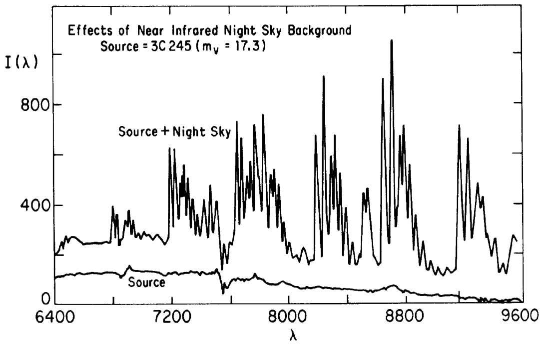

FIG. 2. The effects of night-sky OH emission bands in the near infrared at Kitt Peak National Observatory are vividly illustrated in this spectrum of the QSO 3C 245 obtained with the KPNO 4 m telescope and Cryogenic Camera. The effective entrance aperture was 2.4 arcsec square. The combined spectrum is dominated by the OH emission bands even for this relatively bright source and small entrance aperture. In addition to being strong, the OH is also highly variable. Absorption features due to atmospheric O_2 are visible near 6800 and 7600 Å. Nonlinearities in the wavelength scale have not been removed from the plot, nor has the instrumental response been removed. The estimated sky background at orbital altitudes higher than 200 km would be about 4 units on the plotted scale at 8000 Å.

Although the number of published observations of the night sky from space remains small, the dominant contributors to the continuous background are reasonably well understood (e.g., Paresce and Jakobsen 1980). At wavelengths longer than 3000 Å, zodiacal scattering of sunlight dominates and has a spectral energy distribution like that of the Sun. At shorter wavelengths, diffuse galactic light (DGL)—i.e., galactic starlight scattered by dust grains in the interstellar medium—becomes important. The ratio of the zodiacal to the DGL background is a strong function of wavelength and of position in the sky with respect to the Sun, ecliptic, and galactic plane. Background from unresolved galactic stars will not be important at the high galactic latitudes and the spatial resolutions ($\lesssim 1$ arcsec) under consideration here.

We have evaluated the space sky continuum for a direction that might be typical of extragalactic observations: galactic latitude $b \geqslant 40°$, helioecliptic longitude 150°, and ecliptic latitude 30°. We take the surface brightness of the zodiacal background in the V band from the tabulation of Levasseur-Regourd and Dumont (1980), who give $S_{10}(V) = 90$ at this position. Since one S_{10} unit corresponds to $\mu(V) = 27.78$ mag arcsec^{-2}, this implies $\mu_\lambda(5500) = 22.9$ mag arcsec^{-2}. We assume that the relative energy distribution ($\mu_\lambda[\lambda] - \mu_\lambda[V]$) of the zodiacal background is identical to that of a G2 V star; for $\lambda < 3300$ we adopt the mean of the energy distributions for G2 V stars plotted in the *IUE Ultraviolet Spectral Atlas* (Wu *et al.* 1983), while for longer wavelengths we adopt the mean of the G0–5 V group given in O'Connell (1973). Below 1800 Å, the spectra are poorly determined, but it turns out that the zodiacal background is not important there.

To evaluate the DGL, we turn to the study of Lillie and Witt (1976), which was based on *OAO-2* observations. They quote DGL values in $S_{10}(\lambda)$ units, which is the number of A0 V stars with $m_v = 10$ per square degree required to produce the same surface brightness at any wavelength. In order to convert to surface brightnesses in our monochromatic units, we use the energy distribution for α Lyrae given by Code and Meade (1979); this yields, for example, S_λ (2040 Å) $= 3.9 \times 10^{-20}$ erg s^{-1} cm^{-2} Å^{-1} arcsec^{-2} for S_{10}(2040 Å) $= 1.0$.

The DGL is brighter at lower galactic latitudes and at wavelengths shorter than 1600 Å. In fact, the *OAO-2* data at high latitudes, after correction for background, yields zero or negative fluxes for the DGL at 1910 and 2040 Å. In order to estimate the DGL contribution for $b \gtrsim 40°$, we have assumed that the ratio S_λ (2040 Å)/S_λ (1550 Å) remains constant for $b > 10°$, which yields $S_{10}^{\rm DGL}$(2040 Å, $b > 40°$) ~ 2.4.

The total night-sky background is then the sum of the zodiacal and DGL components. For the direction chosen, the DGL and zodiacal components are comparable at 2500 Å, and DGL dominates at shorter wavelengths. The minimum background level obtained is $\mu_\lambda^{\rm space} = 26$ mag arcsec^{-2} at 2000 Å. This, and the value plotted for λ 1500, may actually be conservative, since more recent measurements by the Berkeley *EUV/FUV Shuttle Spectrometer* yield background values of $\sim$250 photons s^{-1} cm^{-2} Å^{-1} sr^{-1}, corresponding to $\mu_\lambda \sim 26.6$ mag arcsec^{-2}, for $\lambda\lambda$ 1450–1850 in directions with hydrogen column densities $\lesssim 3 \times 10^{20}$ cm^{-2} (Hurwitz, Martin, and Bowyer 1987; Bowyer 1987).

IV. GROUND VERSUS SPACE: THE POTENTIAL OF ULTRAVIOLET SURFACE PHOTOMETRY

The resulting sky-background energy distributions are plotted in Fig. 1. As is evident from the foregoing, these cannot be considered particularly well determined, but we believe they are representative enough to support the basic point of this paper. The relatively flat ground-based sky energy distribution for $\lambda < 5500$ Å may surprise readers who are familiar with quoted sky-background levels at the B band which are up to 1 mag fainter than at V. The difference arises simply because of the absolute flux units adopted for Fig. 1: the B,V system is normalized to the energy distribution of an A0 V star, and the conversion to our system is $\mu(B) - \mu(V) = \mu_\lambda(4400) - \mu_\lambda(5500) + 0.59$ (e.g., Kurucz 1979).

It is clear that space offers a considerable advantage over the ground in sky darkness. This amounts to only ~ 1 mag arcsec^{-2} for $\lambda\lambda$ 4000–6000 but increases rapidly to both longer and shorter wavelengths. As noted in Sec. II, the high brightness levels for $\lambda > 7000$ Å on the ground are produced mainly by strong OH emission. By 10 000 Å, the ground-based sky is estimated to be over 50 times brighter than in space. This has obvious implications for the relative effectiveness with which one can make observations of high-redshift galaxies, for example (cf. Wright 1985). We will not pursue this area here, however, preferring to focus on the ultraviolet instead.

The space background near 2000 Å in Fig. 1 ($\mu_\lambda = 26$ mag arcsec^{-2}) is 4 mag arcsec^{-2} (a factor of 40) darker than at any wavelength on the ground. Backgrounds this faint or fainter (see Sec. III) should be typical of extragalactic pointings. This far-UV minimum in the sky background represents an important new "window" for the study of extragalactic phenomena. Unfortunately, owing to the strong dependence of DGL on galactic latitude, many interstellar-medium studies will be subject to higher UV backgrounds.

The implications of these very low background levels for specific applications depend on a number of factors, including the telescopes and detectors employed, the area and structure of the sources, whether one is making continuum or emission-line observations, and so forth. However, useful rules of thumb may be obtained from the extensive experience of workers at visible wavelengths.

In situations where photon noise is not important and the sky background dominates the photometric uncertainty—e.g., in surface photometry of the outer parts of large nearby galaxies—the limit of current ground-based techniques is $\mu(V) \sim 28$–29 mag arcsec^{-2} (Capaccioli 1987; Schombert 1986a). Schombert quotes rms errors of ± 0.9 mag arcsec^{-2} at $\mu(V) = 29$ mag arcsec^{-2}. Photographic measurements at these levels typically involve the averaging of 5–20×10^3 arcsec^2 of the source and a very large area of the sky background. However, Tyson (1987) has reported 3σ detection isophotes at comparable levels for sources only a few tens of arcsec^2 in size using CCD filter photometry. These limits are 6–7 mag arcsec^{-2} fainter than the sky at the darkest ground-based sites. To be conservative, we will assume that the working threshold for similar surface-photometry problems is 5 mag arcsec^{-2} fainter than (or 1% of) the sky background.

This threshold for large-area continuum surface photometry in space is plotted as a function of wavelength in Fig. 3, and we see that $\mu_\lambda^{\rm LIM} \sim 29$–31 mag arcsec^{-2} for $\lambda < 3000$ Å. Since stars exhibit an enormous range in UV$-V$ colors, one

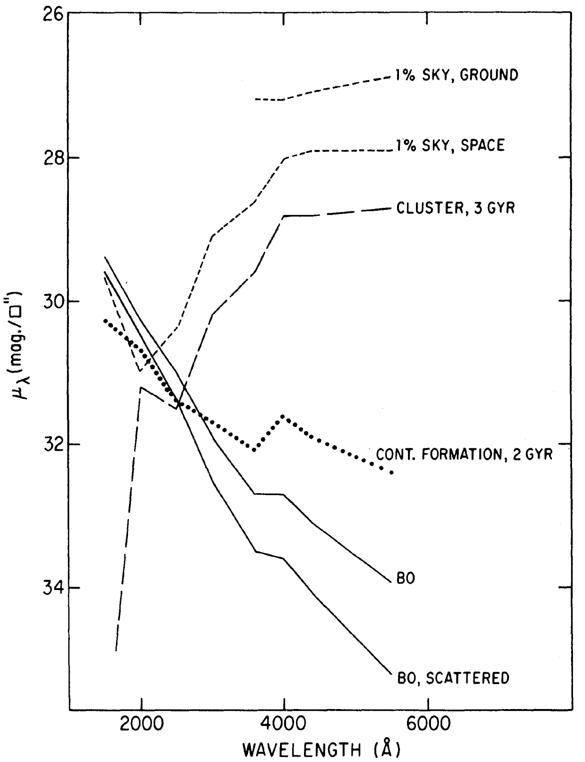

FIG. 3. The usefulness of UV surface photometry for applications to several types of potential targets may be judged from this figure. The short-dashed curves indicate 1% of the ground-based and space-based sky backgrounds as plotted in Fig. 1. This represents a conservative estimate of the working threshold for large-area surface photometry where sky background is the limiting consideration. The other curves are the spectral energy distributions of several likely types of extragalactic targets, estimated as described in Sec. IV. They have been adjusted to reach the working threshold in the UV "window" near 2000 Å but have been offset slightly for clarity. By reading these curves at 5500 Å, one can find the level at which V band photometry would be necessary to make the equivalent physical measurement. For the hotter distributions shown, the equivalent level is $\mu(V) \sim 32$–35 mag arcsec^{-2}.

must take the energy distribution of likely targets into account in assessing the potential value of UV photometry near these limits. A simple approach is to estimate μ_λ (5500 Å) for a given target spectral energy distribution that is just at the photometry threshold in the UV. This gives the level at which V band photometry would be necessary to make the same physical measurement. If this is fainter than the adopted ground-based threshold $\mu^{\rm LIM}(V) \sim 27$ (see Fig. 3), then there will be an advantage in doing the problem in space, other factors being equal.

Figures 1 and 3 indicate that *any object with* μ_λ *(2000 Å)*$-\mu(V) < 4$ *is more favorably observed from space.* From Wu *et al.* (1983), we find that this corresponds to main-sequence stars hotter than F8, or bluer than $(B - V) = 0.50$. A large number of potential extragalactic targets readily meet this "blueness criterion," including metal-poor globular clusters (van Albada, de Boer, and Dickens 1981) and spiral and irregular galaxies (e.g., Coleman, Wu, and Weedman 1980; King and Ellis 1985). Surprisingly, even some E/S0 galaxies meet the criterion because of the presence of the "ultraviolet-excess population," which produces a rise in their continua below 2200 Å (e.g., Code and Welch 1979; Oke, Bertola, and Capaccioli 1981). The bluest luminous ellipticals, for example, have μ_λ (2000

Å) $-\mu(V) \sim 3.0$ and μ_λ (1500 Å) $-\mu(V) \sim 2.3$ (e.g., Burstein *et al.* 1987).

To carry this comparison further, we have computed synthetic UV/V spectral energy distributions for various stellar populations with $Z = Z_\odot$ using the stellar library compiled by Fanelli, O'Connell, and Thuan (1987), which is based on the *IUE Ultraviolet Spectral Atlas* (Wu *et al.* 1983). Single-age populations with $t < 4$ Gyr meet the blueness criterion above; an example is shown in Fig. 3 for a 3-Gyr-old star cluster (excluding any hot remnant population). Surface photometry at 2000 Å for such a source is equivalent to visible photometry at $\mu(V) \sim 28.5$ mag arcsec^{-2}. The sharp falloff in the energy distribution of the 3 Gyr cluster for $\lambda < 1800$ Å is due to the absence of stars hotter than A0. Systems experiencing recent ($t < 0.1$ Gyr) star formation are rich in such stars and have overall colors much smaller than the blueness criterion. The 2-Gyr-old continuous star-formation model in Fig. 3 is an example; the equivalent depth of 2000 Å photometry for such a system would be $\mu(V) \sim 32.5$ mag arcsec^{-2}. Significantly fainter limits are reached for an unreddened B0 star energy distribution, where the equivalent depth of 2000 Å photometry would be $\mu(V) \sim 34.5$ mag arcsec^{-2}. The final curve in Fig. 3 represents unreddened B0 starlight after scattering by a dust cloud, using Jura's (1980) formulation, in which $S_\lambda \sim F_\lambda \tau_\lambda a \sim F_\lambda A_\lambda a$, where F_λ is the flux of the B0 star, a is albedo, τ is the optical depth, and A_λ is the extinction of the cloud (expressed in magnitudes). We have taken A_λ's from the Savage and Mathis (1979) UV reddening law. The scattered spectrum is bluer than the incident light, and so the equivalent depth of 2000 Å photometry is $\mu(V) \sim 35.5$ mag arcsec^{-2}, or a factor of over 100 000 times fainter than the ground-based sky.

It is worth emphasizing again that the problems under consideration here are limited by sky brightness, not photon statistics, so the smaller number of photons per erg in the UV is not an important factor in the resulting S/N. Another potential worry is large extinction by dust in the UV, particularly for active star-forming complexes. The Savage and Mathis extinction law yields $E(2000 - V)/E(B - V) \sim 5.5$, for example. While large extinctions will certainly limit applications of UV photometry in some cases, one finds that many objects of interest, including giant H II regions, irregular galaxies, and blue compact galaxies have surprisingly small extinctions of order $E(B - V) \sim 0.1$–0.3 and are UV-bright (e.g., Huchra *et al.* 1983; Rosa, Joubert, and Benvenuti 1984; Fanelli, Thuan, and O'Connell 1987). Recall also that we have adopted a working threshold of 1% of the UV sky brightness for these estimates but that ground-based experience suggests it may be possible to do accurate photometry at deeper levels. Thus, one expects that the very faint equivalent thresholds quoted above, $\mu(V) > 32$ mag arcsec^{-2}, will be achievable in practice in many cases.

V. APPLICATIONS TO CIRCUMGALACTIC REGIONS

The very dark UV sky is of special interest for a large and rapidly growing class of problems involving the faint outer parts of galaxies. Circumgalactic material has been detected in many forms: cool, neutral hydrogen around both spirals and ellipticals; multiple-absorption-line systems in QSOs suggesting the presence of halos extending up to 100 kpc in radius; hot coronae producing x-ray emission or UV absorption lines; filamentary nebulae (outflows?) along the minor axis of starburst systems; low-surface-brightness shells surrounding early-type galaxies; tidal debris enveloping interacting systems; and finally, of course, dark matter. These regions can clearly provide important information on a number of basic evolutionary processes in galaxies—including tidal interactions, mergers, infall, accretion, and galactic winds—but because of their faintness they have proven difficult to study.

The faint thresholds we calculated in Sec. IV should be applicable to many of these problems. Note that in the case of relatively smooth light distributions, even modest changes in the limiting threshold for surface photometry can greatly increase the area of each Disney galactic "iceberg" that can be studied. In Disney's (1976) formulation of de Vaucouleurs' general brightness distribution functions, we have $\mu(r) - \mu(0) = 2.5\,(r/\alpha)^{1/\beta}$, where α is a length scale and $\beta = 1$ for disks but $\beta = 4$ for spheroids. The area available for surface photometry above a threshold $\mu^{\rm LIM}$ then scales as $A \sim [\mu^{\rm LIM} - \mu(0)]^{2\beta}$. Since $\mu^{\rm LIM}(V) \sim 27$ mag arcsec^{-2} on the ground but the equivalent $\mu^{\rm LIM}(V)$ in space can reach 32–35 mag arcsec^{-2}, depending on circumstances, very dramatic improvements in the areal coverage of galaxies are possible with UV photometry, especially in the spheroidal case.

The circumgalactic remnants of tidal encounters or mergers are likely to include recently formed stars if either of the pair of objects was originally a hydrogen-rich disk (e.g., see the review by Schweizer 1986). In this case, the relevant UV/V energy distribution will most probably lie somewhere between those for the 3-Gyr-old cluster and the 2 Gyr continuous-formation system in Fig. 3, with equivalent V band limits of $\mu^{\rm LIM}(V) \sim 29$–32 mag arcsec^{-2}. Note that even relatively old encounters can still be studied to advantage in the UV.

It is possible that the cool components surrounding some galaxies contain significant amounts of dust, which could then scatter hot starlight from the main body of the galaxy and yield UV/V energy distributions similar to the lowest curve in Fig. 3. This situation has apparently already been encountered in the case of the very low-surface-brightness, cool outer hydrogen arms in M101 (Donas *et al.* 1981; Stecher *et al.* 1982a), which were detected in the 21 cm line and the ultraviolet but not in the visible. This was, in fact, a practical demonstration of the potential of UV imaging for study of low-surface-brightness regions. The 14″ aperture prototype of the *Astro* Ultraviolet Imaging Telescope (Stecher *et al.* 1982b) reached a threshold of μ_λ (2250 Å) ~ 27 mag arcsec^{-2} for regions 10×30 arcsec in size in an exposure time of only 1 min.

Using Jura's (1980) treatment for light scattering in dusty galaxy halos and assuming a UV albedo of ~ 0.5, the limiting neutral-hydrogen column density reached by λ 2000 photometry at the 1% sky level is given by $N_{\rm H}^{\rm LIM} \sim 2 \times 10^{18}$ $\phi^2 (F_\lambda(V)/F_\lambda(2000))\ {\rm dex}[0.4(m_v - 12)]$ cm^{-2}, where ϕ is the angular distance from the galaxy center in arcmin, m_v if the integrated V magnitude of the galaxy, and F_λ is the mean spectral energy distribution of the galaxy. We have assumed a normal gas-to-dust ratio. For Scd galaxies, $F_\lambda(V)/F_\lambda(2000\ \text{Å}) \sim 1$, while for Irr galaxies it is smaller than 1 (King and Ellis 1985). The limiting column densities for relatively bright galaxies, $\sim 10^{18-19}$ cm^{-2}, compare favorably with the limits possible with current 21 cm techniques and long integrations.

A final application of UV surface photometry in this area is to emission lines produced by hot galactic coronae, with

$T \sim 10^{5-6}$ K. Among the expected detectable emission lines in the dark UV window are C IV λ 1550 and C III] λ 1909 (Deharveng *et al.* 1986); O VI λ 1034 is also predicted to be bright (Edgar and Chevalier 1987) but is difficult to observe because of the declining FUV reflectivity of optical coatings and the difficulty in filtering out geocoronal Lyα emission (practical UV filter materials do not yield strong long-wavelength suppression). Another possible method of studying halo gas is to search for photons from the disks of galaxies which have been resonantly scattered by species such as H I and C IV (Smith 1985; Martin 1986). The predicted line intensities are marginally detectable. All of these emission-line applications require reasonably high-spectral-resolution devices.

VI. DETECTION OF DWARF AND OTHER LSB GALAXIES

In this and the next section we consider applications that involve the initial *recognition* of objects with very low surface brightnesses. This is a problem distinct from that of precise photometry of known objects, as discussed above, and the thresholds will therefore differ. The lowest-surface-brightness galaxies known to date have been detected with ground-based Schmidt telescopes with low focal ratios and emulsions with high S/N response at the threshold (e.g., IIIa-J).

The current working limit appears to be a mean surface brightness of $\langle\mu\rangle^{\rm LIM} \sim 25$–26 mag arcsec^{-2} in the B or V bands (Binggeli, Sandage, and Tammann 1985; Schombert 1986b), which is 3–4 mag arcsec^{-2} fainter than the sky. Applying this rule of thumb to the space ultraviolet, we estimate that $\langle\mu_\lambda\,(2000\,\text{Å})\rangle^{\rm LIM} \sim 29$–30 mag arcsec^{-2} for the recognition of low-surface-brightness galaxies.

The density of low-surface-brightness dwarf galaxies should increase rapidly, perhaps exponentially, for integrated $M_B > -17$ (Sandage, Binggeli, and Tammann 1985), implying that this kind of improvement in the working threshold will permit a much deeper probe of the dwarf population. It is not yet known what fraction of the dwarfs will meet the blueness criterion described in Sec. IV. Dwarf Irr's constitute $\sim 20\%$–30% of the dwarf population (Sandage, Binggeli, and Tammann 1985), and these will certainly meet the criterion, probably with energy distributions comparable to the 2 Gyr continuous-formation model shown in Fig. 3. Such objects would be detectable to an equivalent $\mu(V) \sim 31$ mag arcsec^{-2}. Dwarf ellipticals will have much redder energy distributions. Significantly reduced metallic-line blanketing would produce bluer energy distributions than for gE galaxies, but this effect may be counterbalanced by a decrease in the strength of the "ultraviolet-excess population" (e.g., Burstein *et al.* 1987). Even if the far UV does not prove favorable for the detection of dE's, Fig. 1 indicates that there will nonetheless be appreciable gains made at longer wavelengths by telescopes in space.

The detectability of very compact blue dwarf galaxies may also be improved. These are often mistaken for foreground stars or background luminous galaxies, but their low-surface-brightness halos (e.g., Loose and Thuan 1986) will be more readily recognizable against the faint sky background in space.

There are, of course, other species of low-surface-brightness (LSB) galaxies which are not dwarfs (e.g., Romanishin, Strom, and Strom 1983) and whose detectability will be greatly enhanced in space. An excellent example of the surprises that may be in store is the remarkable LSB object Malin 1 recently found by Bothun *et al.* (1987), which has a central disk surface brightness of only $\mu(V) = 25.7$ mag arcsec^{-2} but an integrated disk luminosity of $M_B \sim -22$, which makes it comparable to the most luminous known spirals and QSO host galaxies. As Bothun *et al.* (1987) point out, Malin 1 would have a diameter of 1° if at the distance of the Virgo cluster, and such objects would be extremely difficult to detect except by wide-field imaging against a dark sky.

VII. DETECTION OF PRIMEVAL GALAXIES

Searches for a wide range of plausible types of primeval galaxies have yielded negative results (see the review by Koo 1986). Despite initial pessimism, however, the detection of some high-redshift galaxies by their strong Lyα emission lines has more recently been proven feasible by several groups using narrowband interference-filter CCD imagery (Djorgovski 1987). McCarthy *et al.* (1987) argue that a turbulent, extended Lyα cloud surrounding 3C 326.1 is, in fact, a galaxy in the process of formation at a redshift $z = 1.825$. The continuum radiation from such objects has proved to be very faint, and the equivalent width of the Lyα emission line can reach the remarkable value of 1000 Å in the observer's frame. The effective surface brightness of the 3C 326.1 cloud in the FWHM = 90 Å filter employed for Lyα was $\langle\mu_\lambda\rangle \sim 23.5$ mag arcsec^{-2}, which is 10 times fainter than the night sky at Lick Observatory, where the observations were made.

One can exploit the darker sky in space in searches for strong emission-line objects in several ways. With narrowband filters, detection limits will be fainter than on the ground by factors of 1–4 mag arcsec^{-2} (see Fig. 1), depending on the redshift of the source and assuming that photon statistics do not dominate the measurement noise. Alternatively, one could use broadband filters to sample a larger range of redshift at the same surface-brightness threshold as on the ground. Figure 1 indicates that a 1600-Å-wide filter centered at 2200 Å would sample the redshift range $z \sim 0.15$–1.50 for Lyα sources at an equivalent sky-background level fainter than on the ground. The most effective way to do this might be to employ slitless spectroscopy (e.g., grisms), which provides additional useful spectral information and obviates the need for off-band comparison imagery. Grism exposures covering 1400–3000 Å would also be useful in identifying objects in the $z \sim 0.5$–2.3 range by their strong Lyman discontinuities at 912 Å in the rest frame.

Similarly, yet higher-redshift systems ($z \sim 2$–8) might be detectable in this spectral range by their He I and He II resonance lines (584 and 304 Å in the rest frame, respectively) and the corresponding continuum edges. Such objects would have very peculiar far-UV colors and could probably be identified on broadband exposures. The likelihood of detection depends on considerations such as the neutral-hydrogen covering factor, the luminosity function, and extinction by dust, none of which can be meaningfully evaluated at present. However, the dark UV sky background and reduced confusion from cool objects appear to be important advantages over ground-based searches for very high-redshift systems.

VIII. INSTRUMENTAL CONSIDERATIONS

Technical requirements for instrumentation capable of exploiting the dark UV sky evidently include high sensitivity, detectors with low noise, and (at least in the case of circumgalactic applications) wide fields for proper sampling of the sky background. A large range of combinations of these factors are present in the few UV imaging experiments that have been flown or are scheduled for operation in the relatively near future: the *S201* Schmidt camera (Carruthers, Heckathorn, and Opal 1978), the *Very Wide Field Camera* (Courtes *et al.* 1984), the *SCAP 2000* balloon experiment (Donas *et al.* 1981), the *Hubble Space Telescope* Wide Field/Planetary Camera and the Faint Object Camera, and the Ultraviolet Imaging Telescope of the *Astro* missions (Stecher *et al.* 1982b). None of these instruments is ideal for the problems under consideration here. The *HST* Faint Object Camera has the faintest limiting magnitude for point sources, but its detector noise is equivalent to a surface brightness $\mu_\lambda \sim 22.0$ mag arcsec^{-2} in a broadband filter centered at 2750 Å, which is much brighter than the sky background (cf. Fig. 1). Readout noise in the *HST* Wide Field Camera yields a comparable equivalent surface brightness for integration times of 1800 s. The *Astro* Ultraviolet Imaging Telescope has a large field of view and better detector-noise characteristics, equivalent to $\mu_\lambda \sim 25.8$ mag arcsec^{-2} in a broadband filter at 2400 Å in 1800 s. It appears to be the best suited of these instruments for the study of very low-surface-brightness objects. Its photometric precision is, however, limited to about 5% by its photographic detectors, though in this regard it is similar to the ground-based systems traditionally used for large-area surface photometry.

IX. CONCLUSION

The sky background at high galactic latitudes in the space ultraviolet is a factor of 40 fainter than the night sky on the ground, and this represents an important new window for the study of extragalactic phenomena. Taking into account the spectral energy distributions of potential targets, UV photometry may permit detection of regions with equivalent V band surface brightnesses as low as 35 mag arcsec^{-2}, or over 100 000 times fainter than the ground-based sky. We have adopted a working threshold of 1% of the UV sky brightness for these estimates, and this may be conservative. We have discussed a few applications to specific extragalactic problems that benefit greatly from the reduced sky background in space; undoubtedly there are many others. It is important to take these applications into account in designing new generations of space instrumentation. Because of the bright OH emission bands imposed on ground-based observations in the near infrared (0.7–2 μm), a similar situation will hold there, but we have not addressed applications in this domain.

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