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THE LYMAN CONTINUUM IN STARBURST GALAXIES OBSERVED WITH THE HOPKINS ULTRAVIOLET TELESCOPE

CLAUS LEITHERER[1] AND HENRY C. FERGUSON[1,2]
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; leitherer, ferguson@stsci.edu
TIMOTHY M. HECKMAN[1]
Physics and Astronomy Department, Johns Hopkins University, Homewood Campus, Baltimore, MD 21218; heckman@pha.jhu.edu
AND
JAMES D. LOWENTHAL[1,2]
University of California, Lick Observatory, Santa Cruz, CA 95064; james@lick.ucsc.edu
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ABSTRACT

The starburst galaxies IRAS 08339+6517, Mrk 1267, Mrk 66, and Mrk 496 (=NGC 6090) were observed with the Hopkins Ultraviolet Telescope (HUT) during the Astro-2 mission. All four galaxies have radial velocities larger than 5000 km s^{-1}, permitting the measurement of their intrinsic Lyman continuum fluxes redward of the H I absorption edge in our Galaxy. The sample was selected on the basis of having the most favorable conditions for the escape of Lyman continuum photons. Two σ upper limits of $F_\lambda < 7 \times 10^{-16}$ ergs s^{-1} cm^{-2} $Å^{-1}$ were obtained for the flux around 900 Å within the rest frame of each galaxy.

A set of theoretical spectral energy distributions has been calculated. We show that there exists a tight correlation between the continuum luminosity at 900 Å and the total number of photons emitted in the Lyman continuum, which is valid for high- and low-metallicity galaxies and essentially all relevant initial mass functions and star formation histories. Comparison with the observed values suggests that, on average, less than 3% of the intrinsic Lyman continuum photons escape from the program galaxies.

Models for the ionization of the intergalactic medium at high z by young starbursts require a significant fraction of the ionizing radiation to escape from the galaxy. *If* the four galaxies observed by us have properties similar to young galaxies at redshift $z \approx 3$, such galaxies are not likely to provide Lyman continuum photons for the ionization of the early universe.

Subject headings: galaxies: ISM — galaxies: starburst — intergalactic medium — ultraviolet: galaxies

1. INTRODUCTION

Starburst galaxies are a relatively heterogeneous class of objects with star formation rates high enough that they would exhaust their reservoir of molecular gas on a timescale much less than a Hubble time (Weedman 1987). Starburst galaxies include objects such as nuclear starbursts (Balzano 1983), H II galaxies (Terlevich et al. 1991), blue compact dwarf galaxies (Thuan 1991), and infrared-luminous galaxies (Soifer et al. 1987).

Of particular cosmological interest is the effect such early starbursts could have had on the intergalactic medium. Relatively model-independent arguments from metal production suggests that galaxies forming at $z \geq 3$ could be a significant, or even dominant, contribution to the metagalactic ionizing radiation field (Miralda-Escudé & Ostriker 1990; Songaila, Cowie, & Lilly 1990; Shapiro, Giroux, & Babul 1994; Madau & Shull 1996). However, models for the contribution of star-forming galaxies to the UV background depend sensitively on the assumption of how much radiation leaks out of these gas-rich, dusty environments. Direct measurement of the escaping Lyman continuum flux from starburst galaxies with *Hubble Space Telescope* (*HST*) and *IUE* requires redshifts $z > 0.3$, while relatively modest redshifts, $z > 0.015$, are required to separate the starburst Lyman edge from attenuation by the Galactic Lyman edge and converging Lyman series. Such low-redshift galaxies are ideal candidates for observations with the Hopkins Ultraviolet Telescope (HUT), whose free wavelength range extends to 912 Å and below.

In this Letter we report measurements of the Lyman continuum of four starburst galaxies with HUT. In the absence of absorption and scattering by interstellar gas and dust, theoretical models for the spectral energy distribution of young starbursts predict significant emission above and below the Lyman edge. Therefore, a detection of, or a significant upper limit to, the Lyman continuum can constrain the fraction of photons escaping absorption within the galaxy and ionizing the surrounding intergalactic medium.

2. OBSERVATIONS

The observations were performed with HUT on board the Space Shuttle *Endeavor* during the Astro-2 mission in 1995 March. HUT is a moderate-resolution ($R = 400$ at 1200 Å) spectrophotometer operating in the wavelength range 820–1840 Å. A description of the instrument is given by Davidsen et al. (1992), and its in-flight performance and calibration for Astro-2 are described by Kruk et al. (1995).

We observed four galaxies: IRAS 08339+6517, Mrk 1267, Mrk 66, and Mrk 496 (=NGC 6090). A list of program galaxies was created by applying five criteria: (1) no known active galactic nucleus (AGN) activity, i.e., a genuine starburst; (2) large enough redshift ($cz > 5000$ km s^{-1}); (3) large UV flux at 1500 Å from previous *IUE* observations; (4) strong Hα emis-

[1] Astro-2 Guest Investigator.
[2] Hubble Fellow.

TABLE 1

ADOPTED GALAXY PROPERTIES

Object (1)	Activity Class (2)	cz (km s^{-1}) (3)	D (Mpc) (4)	$E(B-V)_l$ (mag) (5)	N_{rec} (s^{-1}) (6)
IRAS 08339+6517	SB nuc	5610	78	0.55	2.3×10^{54}
Mrk 1267	BCG	5780	78	0.58	6.5×10^{53}
Mrk 66	BCG	6530	91	0.00	9.5×10^{52}
Mrk 496	SB nuc	8790	121	0.60	3.6×10^{54}

NOTES.—Col. (2), Activity class: SB nuc, nuclear starburst; BCG, blue compact galaxy. Col. (3), *cz* is the heliocentric radial velocity. Col. (4), Distances *D* were derived with a Virgocentric infall model using $H_0 = 75$ km s^{-1} Mpc^{-1}. Col. (5), $E(B-V)_l$ is the reddening derived from the Balmer decrement. Col. (6), N_{rec} is the number of recombinations measured from the reddening-corrected Balmer lines.

sion; (5) low Galactic extinction. In Table 1 we give some basic parameters of the observed galaxies. The galaxy properties were adopted or derived from the compilation of Margon et al. (1988), Calzetti, Kinney, & Storchi-Bergmann (1994), Calzetti et al. (1995), McQuade, Calzetti, & Kinney (1995), and Storchi-Bergmann, Kinney, & Challis (1995). Optical recombination line fluxes were obtained by those authors through a 22″ aperture for IRAS 08339+6517 and a 14″ aperture for the other three galaxies. These aperture sizes are similar to the HUT entrance aperture of 20″. All four galaxies have metallicities between solar and one-third solar.

Our sample is consciously biased toward having the most favorable conditions for a high escape fraction of UV photons. The strong Hα emission indicates that many ionizing photons are present. From the full sample of UV-bright starburst galaxies presented by Calzetti et al. (1995), the four we have observed are among the highest for their luminosities in the ratio of UV to infrared flux; thus, we have tried to minimize the amount of dust attenuation. Furthermore, the galaxies are rather symmetric and observed essentially face-on, so that the path length of a photon through the disk is minimized.

The combined spectra presented here are in each case the sum of several different observations taken through 12″ and 20″ diameter circular apertures. Because of the uncertainties in centering, the integrated fluxes from the starburst region are probably uncertain at a level of about 30%. Comparisons to optical and *IUE* data may suffer an additional (probably less than 10%) uncertainty because of the extended nature of the emission.

The spectra of the four galaxies obtained with HUT were reduced in the standard way and are shown in Figure 1. The strong emission features seen in the spectra are geocoronal Lyα and Lyβ. IRAS 08339+6517, Mrk 66, and Mrk 496 also have strong intrinsic Lyα emission that is redshifted with respect to geocoronal Lyα. The most prominent absorption lines are due to stellar C IV λ1550 and Si IV λ1400, in particular in IRAS 08339+6517 (see Leitherer, Robert, & Heckman 1995). Further evidence for hot stars comes from strong O VI λ1034, which is a unique indicator of the most massive stars (Walborn et al. 1995).

The continuum of the four galaxies is flat or slowly rising from longer wavelengths toward Lyα. Around or somewhat below Lyα, the spectra turn over and reach the noise level at 912 Å in the rest frame of each galaxy. An enlarged version of the spectral region around the Lyman edge is shown in Figure 2. Our upper limits on the Lyman continuum flux are computed directly from the count rate data. We calculate the background from the total number of counts in the wavelength range 804–905 Å and assume that this remains flat across the wavelength range of the redshifted Lyman continuum (912–940 Å). In actuality, the background may be up to 5% higher in the 912–940 Å range because of the scattering wings of the geocoronal Lyα line. We compute the Lyman continuum flux from the total number of counts between 915 Å and the redshifted Lyman edge for each galaxy. Our upper limits to the Lyman continuum flux correspond to the maximum source count rates such that the formal Poisson probability of detecting *N* or fewer counts from a given source + background rate × time is less than 5%. These "2 σ" limits, converted to flux, are shown as thick solid lines in Figure 2. For all galaxies, the measurements of the Lyman continuum are consistent with no flux above the noise level.

3. COMPARISON WITH MODEL PREDICTIONS

The amount of UV radiation escaping from a starburst galaxy is determined by three parameters: the intrinsic UV spectrum of individual hot stars, the age and mass spectrum of

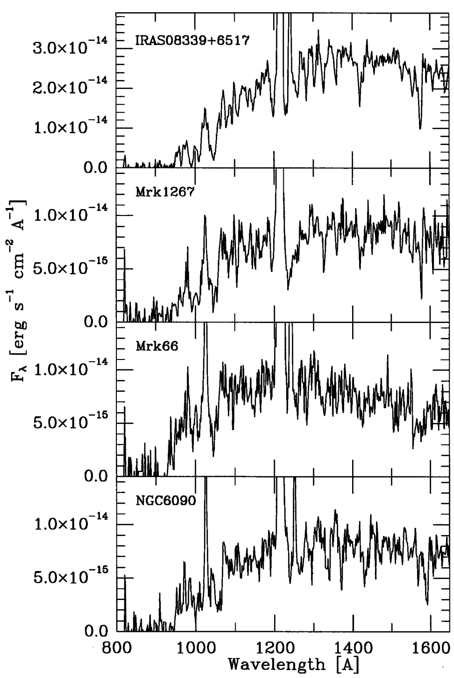

FIG. 1.—HUT spectra of the four program galaxies. Integration times were 3110 s (IRAS 08339+6516), 3238 s (Mrk 1267), 2280 s (Mrk 66), and 3268 s (Mrk 496).

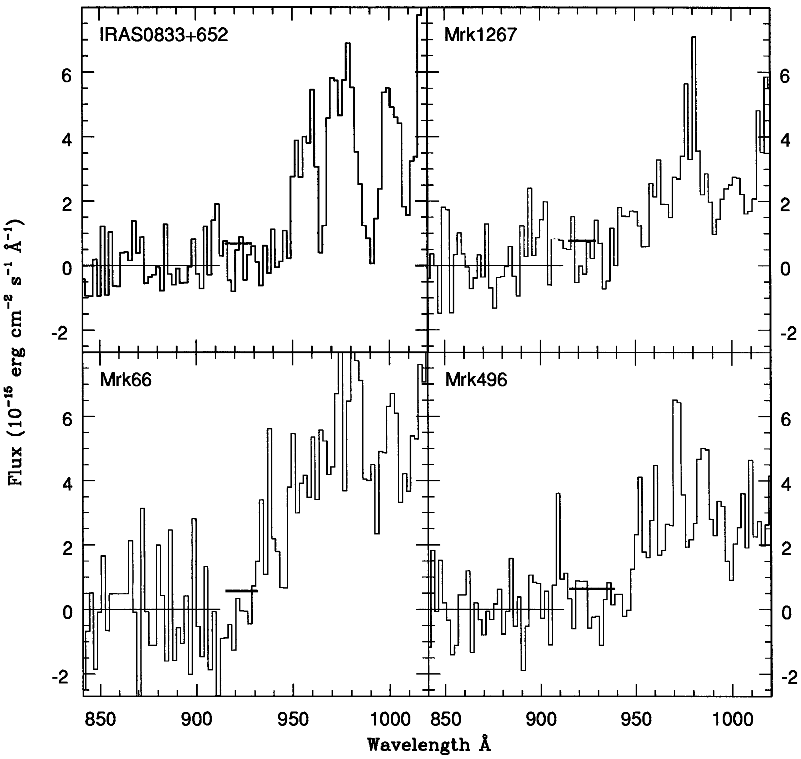

FIG. 2.—Enlarged section of the four spectra of Fig. 1 showing the spectral region around the Lyman discontinuity. The thick horizontal bars in each panel indicate the 2 σ upper limits to the flux measured in the Lyman continuum. The bars span the region between the Galactic Lyman limit at 912 Å and the redshifted Lyman limit of each program galaxy, the wavelength range over which the upper limits were obtained.

the stellar population, and the opacity of the starburst galaxy's interstellar medium.

We used the models of Leitherer & Heckman (1995) to study the relation between the luminosity of the burst population at 900 Å (L_λ) and the total number of Lyman continuum photons ($N_{\rm Ly}$) for different star formation histories and initial mass functions (IMFs). The purpose of these model calculations is to demonstrate that a measurement of L_λ provides a reliable estimate of $N_{\rm Ly}$ even if the starburst parameters are uncertain. The results are in Figure 3. These models were calculated for a constant star formation rate. For all models considered, there is a very narrow relation between L_λ and $N_{\rm Ly}$. We find $\log N_{\rm Ly}/L_\lambda = 13.28 \pm 0.16$ (photons Å erg^{-1}). A second model series was run for an instantaneous burst. The results are essentially the same: $\log N_{\rm Ly}/L_\lambda = 13.07 \pm 0.50$.

The model predictions can be used to derive upper limits on the fraction of Lyman photons escaping from the galaxies. Using the observed upper limits of F_λ in column (2) of Table 2, the distances of Table 1, and correcting for Galactic foreground absorption (col. [3] of Table 2), we obtain lower limits on $\log N_{\rm rec}/L_\lambda$. They are tabulated in column (4) of Table 2.

Comparison with the model predictions of Figure 3 implies that the observed L_λ is much lower than expected if every ionizing photon escaped from the galaxy. If the emission is isotropic, the fraction of photons below 912 Å escaping ranges from less than 15% in Mrk 66 to less than 0.95% in Mrk 496 (see col. [5] of Table 2).

Absorption by gas and/or dust in the galaxies and in their halos may be responsible for the low fraction of photons escaping. Dust scattering is not likely to be important since the HUT aperture is large enough to encompass all the dust scattering regions. The data do not allow us to quantify the relative importance of gas and dust absorption. The decreasing continuum level below 1100 Å in all galaxies suggests that interstellar dust absorption is significant.

Most of the Lyman continuum photons from a representative hot-star population are emitted at wavelengths within

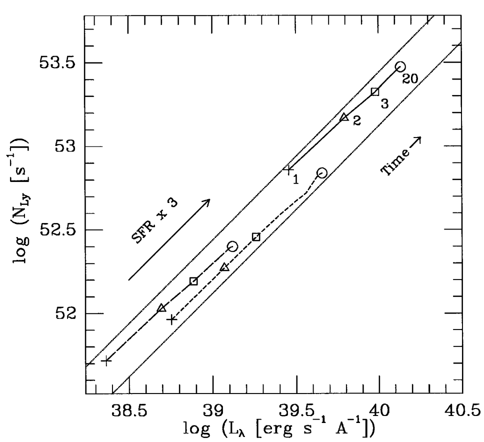

FIG. 3.—Total number of Lyman continuum photons, $N_{\rm Ly}$, vs. luminosity at 900 Å, L_λ, for a constant star formation rate of 1 $M_\odot$ yr^{-1}. Three models are considered: a Salpeter IMF with power-law exponent 2.35 and upper and lower mass cutoffs of 100 and 1 $M_\odot$, respectively (*solid line*), an IMF with exponent 3.3 and the same cutoff masses (*long-dashed line*), and a Salpeter IMF truncated at 30 $M_\odot$ instead of 100 $M_\odot$ (*short-dashed line*). Symbols indicate time past the onset of star formation: 1 Myr (*crosses*), 2 Myr (*triangles*), 3 Myr (*squares*), and 20 Myr (*circles*). The dotted lines from bottom left to top right give the upper and lower limits of the relation $\log N_{\rm Ly}/L_\lambda = 13.28 \pm 0.16$.

TABLE 2

GALAXY PROPERTIES DERIVED WITH HOPKINS ULTRAVIOLET TELESCOPE

Object (1)	F_λ (ergs s^{-1} cm^{-2} Å^{-1}) (2)	A_{910} (mag) (3)	log N_{rec}/L_λ (photons Å erg^{-1}) (4)	f_{esc} (5)
IRAS 08339+6517....	$<6.9 \times 10^{-16}$	1.25	>15.2	<1.7%
Mrk 1267.............	$<7.7 \times 10^{-16}$	1.23	>14.6	<4.8
Mrk 66................	$<5.6 \times 10^{-16}$	0.41	>14.1	<15
Mrk 496...............	$<6.4 \times 10^{-16}$	0.48	>15.3	<0.95

NOTE.—Col. (2), F_λ is the 2 σ upper limit on the flux at about 900 Å observed with HUT. Col. (3), A_{910} is the total Galactic foreground absorption at 910 Å, derived from the observed H I columns (Stark et al. 1992), $N_H/E(B-V) = 4.93 \times 10^{21}$ cm^{-2} mag^{-1} (Diplas & Savage 1994), and the Mathis 1990 extinction curve. Col. (4) is the derived lower limit on log N_{rec}/L_λ. L_λ has been reddening-corrected with A_{910} of col. (3). The escape fraction of photons f_{esc} in col. (5) was obtained by dividing 13.3 (see Fig. 3) by the observed values in col. (4).

100–200 Å of the Lyman break. This coincides with the wavelength of the largest neutral hydrogen opacity. Additionally, dust absorption becomes important toward shorter wavelengths. Both effects together make it unlikely that a significant fraction of photons escapes from the galaxies at wavelengths shorter than those observed by HUT.

Absorption of photons may occur either in the starburst itself or, in addition, in a surrounding halo. Thus, our measurements do not exclude the possibility of the ionization of a halo by the diffuse radiation field escaping from the starburst.

4. IMPLICATIONS FOR THE ULTRAVIOLET BACKGROUND RADIATION

These are the first direct measurements of the emergent UV flux from actively star-forming galaxies, and the implications for both galactic structure and cosmology are significant. The results represent an important first step toward understanding whether or not young, star-forming galaxies might be responsible for the ionization of the early universe. At present, the known population of QSOs at high redshift appears to fall short by about a factor of a few from being able to ionize the intergalactic medium, which must have happened by at least $z = 4$ judging by the intergalactic medium's transparency (Miralda-Escudé & Ostriker 1990; Meiksin & Madau 1993). Fall & Pei (1995) showed that this apparent shortfall may be a consequence of dust obscuration, which leads to an underestimate of the observed comoving density of quasars. If dust obscuration is taken into account, the contribution of quasars to the mean ionizing background is high enough to be consistent with limits imposed by the proximity effect.

Lyman continuum photons that accompany the production of metals observed in Lyα forest clouds could, in principle, make a significant contribution to the ionizing background at high redshift as well. Such photons could be produced by hot stars formed in young galaxies (Bechtold et al. 1987; Shapiro et al. 1994). The observed metallicity in spirals and elliptical galaxies and the recent detection of C IV absorption lines in Lyα forest clouds by Cowie et al. (1995) and Tytler et al. (1995) can be used to constrain the production of ionizing ultraviolet photons (Miralda-Escudé & Ostriker 1990; Madau & Shull 1996). This estimate is uncertain because of the unknown fraction of Lyman continuum photons escaping from the gas- (and possibly dust-) rich star-forming regions in galaxies. Madau & Shull (1996) found that young star-forming galaxies could account for the background intensity at the Lyman edge, in agreement with the limits imposed by the proximity effect if the photon escape fraction is on the order of tens of percents. This fraction is significantly higher than observed in the four galaxies we studied.

If the four observed galaxies have properties similar to those of young galaxies at high redshift, they are unlikely to provide a significant contribution to the UV background radiation.

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