A POSSIBLE FIRST MEASUREMENT OF THE INTERGALACTIC INFRARED RADIATION FIELD

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The determination of the intergalactic infrared radiation field (IIRF) is of the utmost importance to deductions about how young galaxies form and evolve. All of the critical astrophysical processes involved, emission of infrared radiation from the cool photospheres of the now older star population, followed by dust reradiation of starlight at longer wavelengths and subsequent redshifting of the infrared radiation to even longer wavelengths, have focused interest on this unexplored region of the electromagnetic spectrum. We have previously proposed[1] a new way of using ground-based observations to look for absorption in the high energy spectra of γ-ray blazars to probe the IIRF. Applying our method to the observed spectrum[2,3] of the BL Lac object Mrk421, we find evidence for a high-energy cutoff consistent with absorption by an IIRF which is of the magnitude expected to be produced by stars and dust in galaxies[1,4] with at least 30 percent of the energy from stellar nucleosynthesis terminating in the infrared. The sharpness of the cutoff is not consistent with that from any known source emission mechanism. Our result on the magnitude of the IIRF rules out exotic non-stellar emission processes and puts constraints on theories of early galaxy evolution.

The magnitude and spectrum of the cosmic infrared radiation field have long been recognized by cosmologists and astrophysicists as crucial empirical data for determining information about the early evolution of galaxies such as the formation rate of late-type stars in old stellar populations and the rate of nucleosynthesis of heavy elements in stars leading to the formation of interstellar dust. Unfortunately, observational determinations of the IIRF are plagued by the difficulty of separating this radiation from galactic foreground radiation and zodiacal light. Direct observations have only produced upper limits on the IIRF which lie far above theoretical expectations[5]. However, the IIRF can be probed by looking for absorption of very high energy γ-rays in the spectra of blazars[1]. The absorption process involves the collision of a γ-ray photon from the blazar with a

photon of the IIRF. In the collision, both the γ-ray and the IR photon disappear and their energy reappears in the form of an electron-positron pair.

Observations of high energy (GeV) γ-rays from blazars have been made by the EGRET detector on the Compton Gamma Ray Observatory satellite. Observations of very high energy (TeV) γ-rays can be made by using ground-based Cherenkov detectors to observe the light from γ-ray induced atmospheric air showers[6]. We have recently used such observations to place conservative upper limits on the IIRF and rule out exotic mechanisms for its production[7]. In this Letter, we attempt to go further, interpreting the observed dearth of photons above 3.4 TeV in the Whipple data as most reasonably being *prima facie* evidence for absorption by the IIRF and thereby providing a first estimate of its magnitude.

We have previously stated that simultaneous satellite and ground based observations would generally be desirable in order to accurately determine the spectral characteristics of a source[1]. However, in the case of Mkr 421, simultaneous observations do not appear to be required. Although the Whipple[2] and EGRET[3] observations were not simultaneous, averaging over the observing period of several weeks were needed to obtain the Whipple data, resulting in at most a 20% variation in the Mkr421 flux between 1992 and 1993[8]. Also, the EGRET observations have shown no evidence of changes in the spectral index of blazar sources for which the total flux is known to be highly variable. Both of these points, together with the excellent fit of the data to a single power-law over the whole energy range from 70 MeV to TeV energies, give us confidence that, in this case, we have a good spectral determination.

The differential energy spectrum of Mkr421, obtained from both EGRET and Whipple observations[2,3] is given by[7]

$$I(E) = (1.02 \pm 0.14) \times 10^{-11} E^{-2.06 \pm 0.04} \text{ photons/cm}^2\text{/s/TeV} \tag{1}$$

up to and energy of $\sim$ 3 TeV. In our previous analysis[7], the spectral information above

3.4 TeV was neglected. However, here it is just this data which play a key role in our determination of the IIRF. Using Table 1 of ref. 2, and extrapolating eq. (1), we expect $\sim$ 58 ON-source events (source γ-rays and cosmic-ray background) above 3.4 TeV, whereas only 26 ON-source events were observed, consistent with the 27 OFF-source cosmic ray background events collected with similar exposure. Furthermore, above 5.1 TeV we expect $\sim$ 32 ON-events, whereas only 10 are observed against the 12 background events. The significance of this lack of events is $\sim 4\sigma$ when taking the uncertainty in the spectral index into account with a χ^2 fit.

We will interpret this data as being the result of absorption by the IIRF. Consider the interaction of a γ-ray of energy E with a soft photon of energy ϵ. Pair production is expected above the threshold energy condition for generating an electron and a positron, each of mass m, $E\epsilon(1-\cos\theta) > 2(mc^2)^2$, where θ is the angle between the photon directions.

The collision cross section σ for the pair production absorption process, involving a γ-ray of energy E and an infrared photon of energy ϵ, is maximised when

$$\epsilon \simeq \frac{2(mc^2)^2}{E} \simeq 0.5(\frac{1\ \mathrm{TeV}}{E})\ \mathrm{eV}, \tag{2}$$

so that a 1 TeV γ-ray is most effectively absorbed by a K-band infrared photon of energy $\sim 1/2$ eV and wavelength$\sim 2\mu$m.

If the IIRF photon density is n, and the distance to the source is given by $L = cz/H_o$, (where H_0 is taken to be 75 km s^{-1} Mpc^{-1} and z=0.031 for Mkr421), the optical depth for a γ-ray will be roughly $\tau \sim n\sigma L$. The differential energy spectrum I(E) for Mkr 421 given by eq. (1), is assumed to hold true at the source for all energies of interest. We then expect an absorbed differential spectrum of the form $I(E)\exp(-\tau(E))$. We therefore determine the IIRF density n by determining $\tau(E)$ from the spectral data, yielding $n \sim \tau/\sigma L$. For a more exact and detailed description of the calculations, see refs. 1 and 7.

The combined EGRET and Whipple spectral data points were used to construct the integral spectrum shown in Figure 1. From a χ^2-fit, we obtained the best fit spectra (and

hence the parameters for the IIRF) by comparing the observed flux values $F_1, ..., F_{13}$ with the expected flux values obtained using a differential γ-ray spectrum of the form

$$I(E) = KE^{-\Gamma} \exp\left[-\tau(E;\ \kappa, \alpha)\right] \tag{3}$$

The parametric expression which we used for the optical depth is $\tau(E;\ \kappa, \alpha) = a(\alpha)\kappa E^{\alpha-1}$, which was derived using power law spectra for the IIRF of the form $n(\epsilon) = \kappa\epsilon^{-\alpha}$ with the two values for α of 2.0 and 2.55 taken for a galaxy generated IIRF[4]. For $\alpha = 2$ we find $a = 120$, whereas $a = 143$ for $\alpha = 2.55$. The free parameters of the χ^2-fit are K, Γ and κ, given a value for α. The details of the fits are given in the caption of Figure 1. The best fit integral spectra for $\alpha = 2$, and $\alpha = 2.55$ are shown in Figure 1 by the short dashed line and thick solid line respectively.

Since the errors on the spectral index Γ and the IIRF constant (κ) are correlated, we constructed the 1σ and 2σ confidence contours for $\alpha = 2$ (short dashed contours) and 2.55 (solid contours) as shown in Figure 2. The confidence contours indicate the range for κ, given the uncertainty in Γ. The sharpness of the cutoff seen in Figure 1 indicates that $\alpha = 2.55$ is marginally preferred relative to $\alpha = 2$, and for $\alpha = 2.55$ we obtain the best fit spectrum of

$$n(\epsilon) \sim (0.8^{+0.6}_{-0.4}) \times 10^{-3}\epsilon^{-2.6}\left(\frac{H_o}{75\ \mathrm{kms^{-1}Mpc^{-1}}}\right)\ \mathrm{cm^{-3}eV^{-1}}\ \text{ for } 0.01\ \mathrm{eV} \lesssim \epsilon \lesssim 1\ \mathrm{eV} \tag{4}$$

This range is shown by the slanted shaded box in Figure 3.

There are three main caveats which are related to our analysis, *viz.*, (1) There may be some uncertainty in determining the event rate derived by the Whipple group for their highest energy events owing to a possible oversubtraction of assumed proton produced events, which can become more confused with γ-ray produced events at higher energies. However, we note that the Crab nebula was observed by Whipple group to have a power law spectrum with no rollover reported up to 10 TeV. The Whipple spectra of the Crab and MKr421 both connect smoothly with the EGRET spectra[2,9], suggesting that other

systematic effects may not be too much of a problem in the analysis of the Whipple data. (2) The source spectrum may have an intrinsic turnover above $\sim$ 3 TeV. However, one may then ask why the turnover would occur at exactly the energy expected for an IIRF absorption effect. We also note that emission models involving Compton scattering of high energy electrons in the source would not produce such a sharp cutoff[10-12]. (3) Intrinsic absorption in the source may cause the high energy cutoff. However, we consider it somewhat improbable that the infrared characteristics of the source would conspire to produce an absorption feature which would exactly mimic that which would be produced by a resonably estimated IIRF. We also note that if the absorption is intrinsic to Mk421, our estimate of the IIRF becomes a strong upper limit which can be used to constrain galaxy evolution models.

Therefore, we conclude that our result may indeed be the first determination of the IIRF at a level which is expected from theoretical arguments[1,4]. Our roughly derived IIRF spectrum suggests that the IIRF arises from stellar processes in galaxies[7] and that, on average, at least 30 percent of the total energy released in stellar nucleosynthesis (including that from IR and starburst galaxies) eventually winds up in the infrared wavelength band. Finally, we note that if the IIRF, and thus n can be directly measured, as may eventually be possible with the DIRBE experiment on the COBE satellite[13], we may be able to obtain a new measurement of the Hubble constant $H_o \propto n/\tau$ at cosmologically significant distances[14].

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Figure Captions

Figure 1: The Mrk421 integral γ-ray energy spectrum from EGRET[3] and Whipple[2] observations compared to theoretical spectra corresponding to 2.7K absorption only (dotted line) and absorption expected from the upper limits of ref. 9 (long dashed and dot-dash lines). The solid line ($\kappa = 8 \times 10^{-4}$) represents our measured spectrum corresponding to $\alpha = 2.55$. Intergalactic electron-photon cascading,[15,16] which would result in a pile-up towards lower energies, is not expected to influence the TeV spectrum of MKr421, since the source is observed within a field-of-view of $\Delta\theta \sim 10$ arc minutes[2], and it can be shown that an intergalactic magnetic field of $B \sim 3 \times 10^{-19}(E_e/10 \text{ TeV})(\Delta\theta/10')$ G or greater would deflect the cascade TeV electrons (with energy $E_e = 10$ TeV) away from the source direction. Since the measured magnetic field strengths in superclusters[17] are of the order of a μG, it is highly unlikely that the intergalactic field would be as weak as $\sim 10^{-19}$ G. The Tibet air shower upper limit[18] is shown at 30 TeV.

Figure 2: A 2 dimensional contour plot of spectral index Γ versus the IIRF density κ for $\alpha = 2.55$ (solid contours) and $\alpha = 2$ (dashed contours). The cross indicates the best solution for each α (χ^2 per degree of freedom is < 1 in both cases) and the contours are marked by "1" and "2", indicating 1σ and 2σ confidence contours respectively.

Figure 3: The extragalactic infrared background photon density versus energy (after Fig. 1 of Ref. 7). The spectrum corresponding to the maximum contribution from galaxies[4] is shown as a long dashed line. The upper limits derived from direct observation in the optical[19] and the near infrared[20] are shown as indicated. The model estimates by Tyson[21] are shown as crosses and that of Yoshii and Takahara[22] by an open circle. The previous upper limits from TeV observations[9] for $\alpha = 2$ and $\alpha = 2.55$ are indicated as 'Stecker & de Jager'. Our present possible detection is shown as a slanted shaded box labled "This Work".

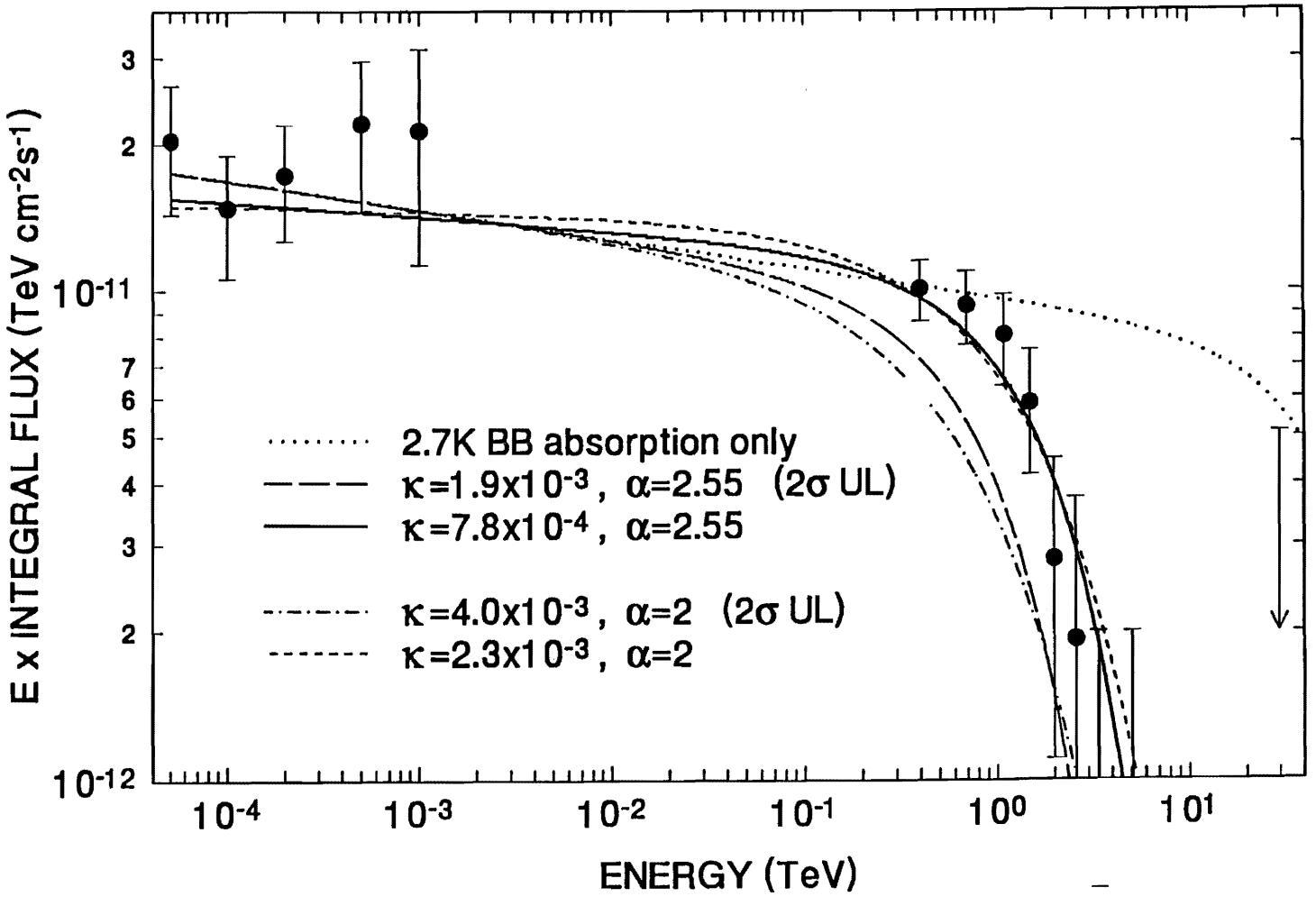
E x INTEGRAL FLUX (TeV cm-2s-1)
3
2
10-11
7
6
5
4
3
2
10-12
10-4
10-3
10-2
10-1
100
101
ENERGY (TeV)
2.7K BB absorption only
κ=1.9x10-3, α=2.55 (2σ UL)
κ=7.8x10-4, α=2.55
κ=4.0x10-3, α=2 (2σ UL)
κ=2.3x10-3, α=2

FIG. 1

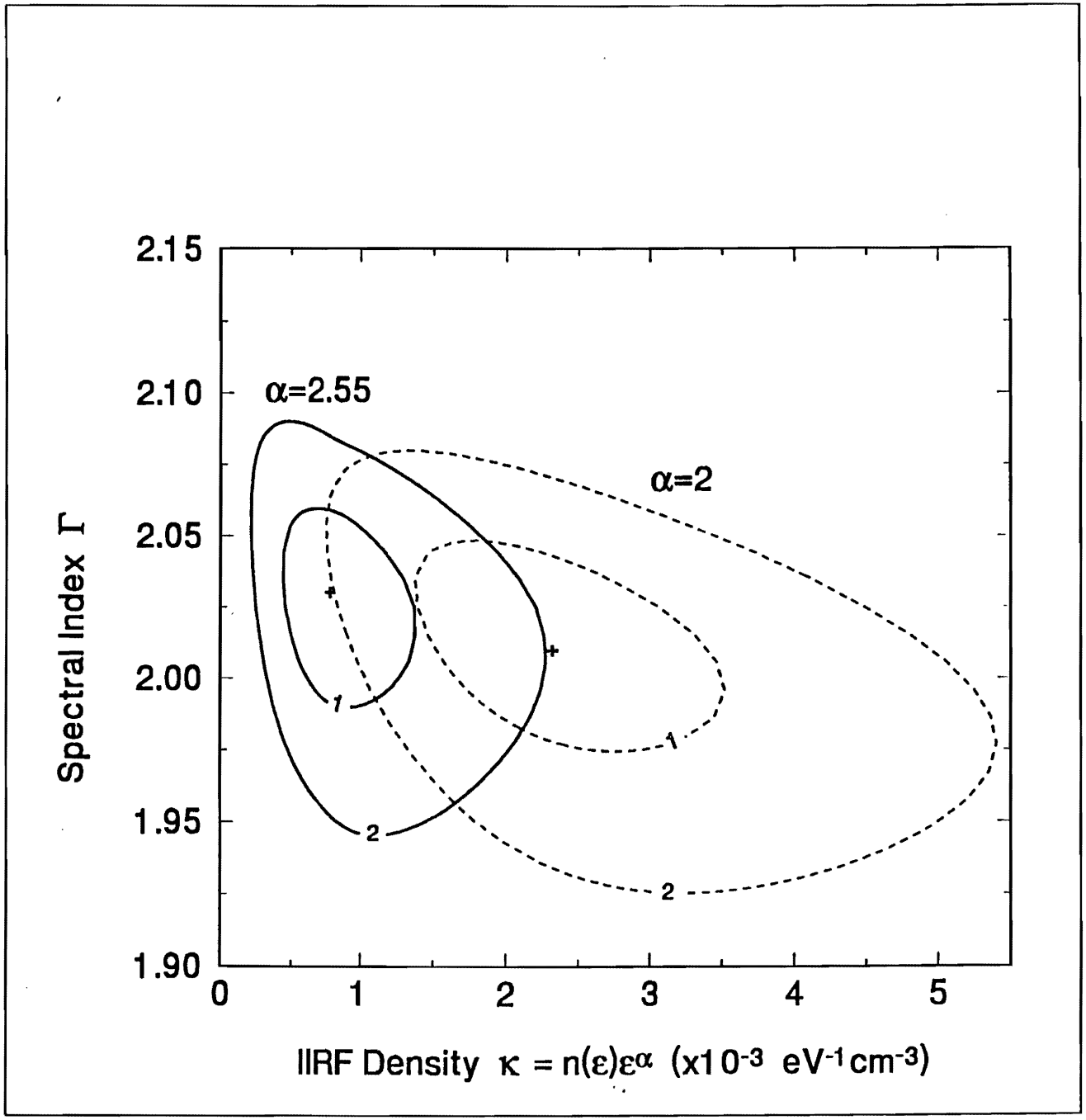
2.15
2.10
2.05
2.00
1.95
1.90
Spectral Index Γ
α=2.55
α=2
1
2
1
2
0
1
2
3
4
5
IIRF Density κ = n(ε)ε^α (x10^-3 eV^-1 cm^-3)

FIG. 2

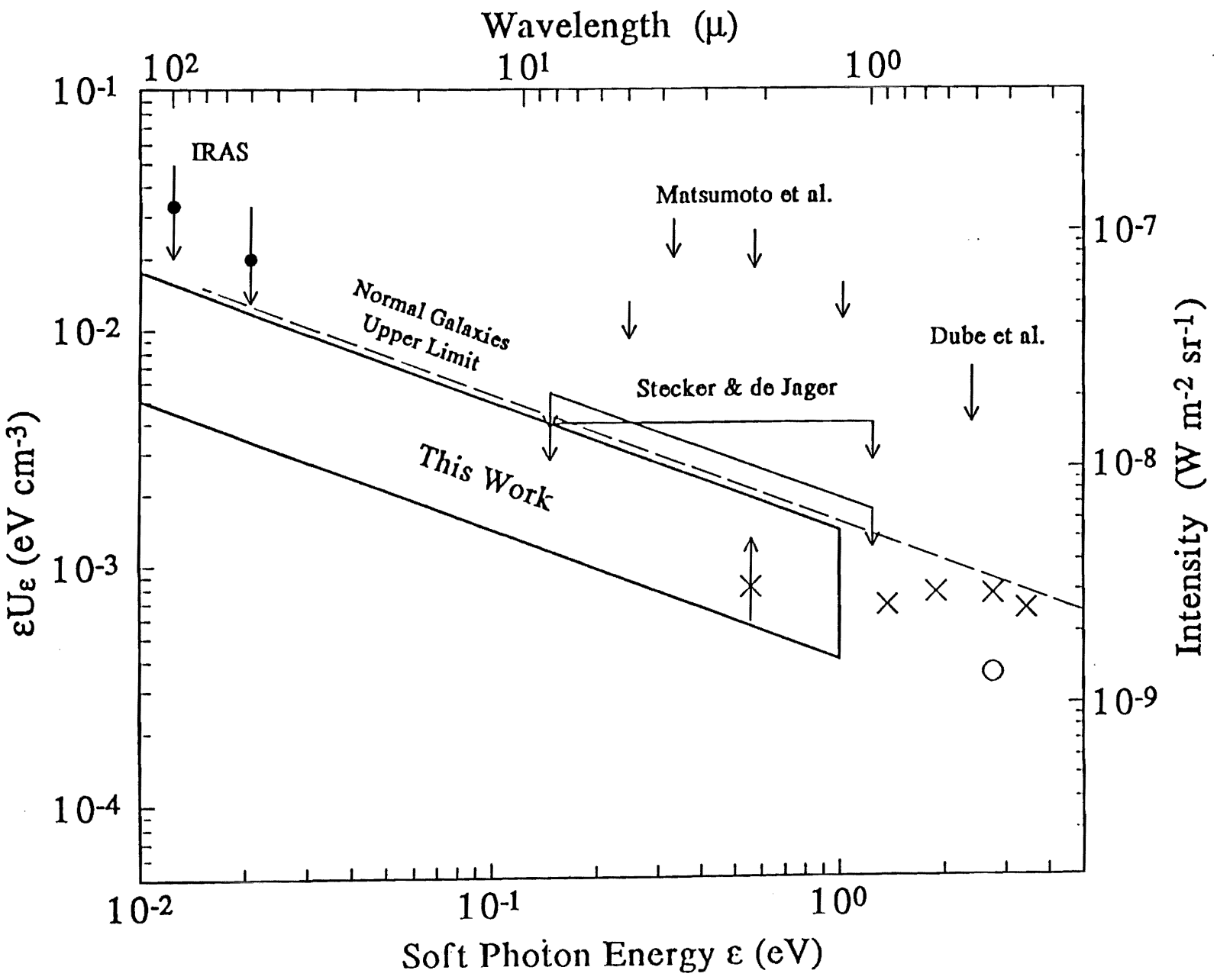
Wavelength (μ)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
IRAS
Matsumoto et al.
Normal Galaxies
Upper Limit
Stecker & de Jager
Dube et al.
This Work
εUε (eV cm^-3)
10^-7
10^-8
10^-9
Intensity (W m^-2 sr^-1)
10^-2
10^-1
10^0
Soft Photon Energy ε (eV)

FIG. 3