Fermi National Accelerator Laboratory

FERMILAB-Pub-92/60-A
February 1992

Cosmological Signatures of Decaying Dark Matter

Scott Dodelson

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
Box 500
Batavia, IL 60510-0500

Jay M. Jubas

Department of Physics
Massachusetts Institute of Technology
Cambridge, MA 02139

The Decaying Dark Matter (DDM) scenario is a viable way of ionizing the Universe at high redshifts. We examine the constraints on this scenario due to the diffuse ultraviolet flux and Gunn-Peterson tests. The former require the decaying particle lifetime to be greater than $\sim 10^{23}$ sec, while the latter require the lifetime to be less than $\sim 10^{24}$ sec. An order of magnitude improvement in either of these observations would therefore have important implications for DDM. We also point out a distinctive signature of DDM: a sharp drop in the infrared part of the spectrum.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

Introduction. Two unresolved problems in the standard cosmological model are the identity of the dark matter and the apparent reionization of neutral hydrogen in the intergalactic medium (IGM). Gunn-Peterson tests show that the amount of diffuse neutral hydrogen in the IGM is significantly lower than the standard model prediction. As an example, the limit imposed by Steidel and Sargent [1] on the intergalactic hydrogen density is $n_{HI} < 8.4 \times 10^{-12} h$ cm^{-3} at a redshift $z = 2.64$. Here h is the Hubble constant today in units of 100 km sec^{-1} Mpc^{-1} and lies between .4 and 1. The standard model prediction for the hydrogen density at this redshift is roughly 7×10^{-6} cm^{-3}, violating the Steidel-Sargent limit by six orders of magnitude.

An intriguing possibility is that a massive neutrino could be both the dark matter which closes the universe and, if the lifetime for the process $\nu_{\rm heavy} \to \nu_{\rm Light} + \gamma$ is in the right range, be the source of radiation which reionizes hydrogen [2]. It is easy to estimate the properties the neutrino must have in order to fill both these roles, i.e. to be decaying dark matter (DDM). First, we require that the photons produced in decays must be able to ionize neutral hydrogen; that is they must have energy greater than $\epsilon_0 = 13.6$ eV. Since every photon carries off energy equal to half the decaying neutrino mass [during the late epoch under consideration, the neutrinos are very non-relativistic], this translates into a lower bound on the neutrino mass: $m_\nu > 27.2$ eV. Second, a well-known upper bound [3] on the neutrino mass [4] follows from the age of the Universe and the observed energy density today. For the sake of concreteness, we take this limit to be $m_\nu < 37.5$ eV [5] Third, since the neutrino must be around today to be the dark matter, its lifetime must be greater than t_0, the age of the Universe. Finally, since most of the hydrogen in the IGM has been ionized, at least as many photons must have been produced in decays as there are hydrogen atoms in the IGM, $n_B(t_0)$. The number of photons produced in such decays is $n_\nu(t_0)t_0/\tau$, where n_ν is the neutrino number density and τ is the lifetime into the radiative mode [assumed the dominant one]. Therefore, the lifetime must be less than $t_0 n_B(t_0)/n_\nu(t_0)$, roughly 10^{27} sec.

In this letter we show that the DDM scenario is severely constrained by the diffuse photon flux, I_0, and by Gunn-Peterson tests. The observational upper limits on I_0 require τ to be greater than $\sim 10^{23}$ sec. Even though most of the hydrogen is ionized in the DDM scenario for lifetimes less than 10^{26} sec, we show that recombination leads to a non-neglible level of neutral hydrogen. In fact, the strictest Gunn-Peterson constraints require τ to be less than 10^{24} sec. Therefore, an order of magnitude improvement in either of these observations will rule out the DDM scenario. These purely "cosmological" limits are not related to those recently discussed by Sciama and collaborators [6]. They have pointed out that if we require the DDM to also provide the flux needed to ionise hydrogen in our galaxy and in Lyman α clouds, then only a very narrow region in parameter space is allowed.

We also point out a distinctive signature of DDM. In the absence of any absorbtion due to ionization, the spectrum coming from a decaying particle is smoothed out today due

to the redshift. Low energy photons were produced earlier while higher energy photons were produced more recently. Absorbtion changes this: Before the Universe is ionized all photons produced in decays are eaten up in the ionization process; that is, the Universe is opaque to them. After ionization is complete, photons produced in decays travel freely. Therefore, the low energy end of the photon spectrum is cut off. If the transition from the un-ionized to the ionized state [i.e. the opaque to the transparent regime] is rapid, and our results show that it is very rapid, then the cut-off in the photon flux today is similarly pronounced.

Neutral Hydrogen Density. The Gunn-Peterson tests are so restrictive that even if DDM manages to ionize most of the intergalactic hydrogen, the small remaining un-ionized component might violate the tests. To compare the predictions of the DDM scenario with observations, it is therefore important to know the predicted value of the neutral hydrogen density as a function of redshift, $n_{HI}(z)$. During all epochs probed by experiment, ionization is sufficiently rapid, so that the rates for ionization and recombination must balance:

$$n_e^2 \alpha(T) = n_{HI} \langle n_\gamma \sigma_{\rm ion} \rangle c \tag{1}$$

where n_e is the free electron number density [assumed equal to the free proton number density]; $\alpha(T)$ is the thermally averaged recombination coefficient [7] which is only mildly temperature dependent, and $\langle n_\gamma \sigma_{\rm ion} \rangle c$ is the ionization rate integrated over the photon distribution. So to determine $n_{HI}(z)$, we must determine the electron density and temperature and photon distribution. If we focus our attention on the regime after most of the ionization has occurred, then the electron density will simply equal the diffuse baryon number density, n_B. Before any clustering has taken place, n_B is equal to the primordial baryon density, which is severely constrained by big bang nucleosynthesis [8]; to a good approximation, then, $n_e = 1.4 \times 10^{-7}(1+z)^3$ cm^{-3}. The photon spectrum coming from a decaying neutrino can be calculated [9]; in the absence of absorbtion, it is:

$$\frac{dn_\gamma}{dE} = \frac{n_\nu(z)}{H(z)\tau} \frac{E^{1/2}}{(m_\nu/2)^{3/2}} \Theta(m_\nu/2 - E) \tag{2}$$

where n_ν is the decaying neutrino number density, $115(1+z)^3$ cm^{-3} and $H(z) = H_0(1+z)^{3/2}$ in the matter dominated, flat Universe under consideration. We can analytically integrate the ionization cross section weighted by this distribution since in this regime, the cross section is simply parameterized by $\sigma_{\rm ion} = 6.3 \times 10^{-18}(\epsilon_0/E)^3$ cm^2. Therefore, the ionzation rate is:

$$\langle n_\gamma \sigma_{\rm ion} \rangle c = 4.4 \times 10^{-12} \frac{(1+z)^{3/2}}{\tau_{24} h} \left[m_{27.2}^{-3/2} - m_{27.2}^{-3} \right] \sec^{-1}, \tag{3}$$

where $\tau_{24} \equiv \tau/10^{24}$ sec and $m_{27.2} \equiv m_\nu/(2\epsilon_0)$. Note that as $m_\nu/2$ goes to ϵ_0 ($m_{27.2} \to 1$), the number of ionizing photons goes to zero, since almost immediately after produced, a

photon redshifts and no longer contributes to the ionizing flux. The only remaining unknown in Eq. (1) is the electron temperature. In a companion paper [10] , we set up and solve the Boltzmann equations to determine $T(z)$; we find that in this late epoch the electron temperature varies very little; typical values are between $1000 - 5000K$. Normalizing to the middle of this range, we find that

$$n_{HI} = 4.1 \times 10^{-15}(1+z)^{9/2}\tau_{24}h\alpha_{3000}\frac{m_{27.2}^3}{m_{27.2}^{3/2}-1}\mathrm{cm}^{-3}, \tag{4}$$

where $\alpha_{3000} \equiv \alpha(T)/\alpha(3000K)$. Due to recombination, the remnant neutral hydrogen density scales as $(1+z)^{9/2}$, not simply as $(1+z)^3$.

This expression for n_{HI} is valid only as long as the assumed form for the photon spectrum, Eq. (2), is valid. But Eq. (2) was derived assuming no absorbtion, i.e. assuming that all photons produced travel freely through the Universe. In fact the probability that a photon produced at epoch z with energy $m_\nu/2$ will be absorbed is simply

$$P(z) = \int_{(1+z)/m_{27.2}}^{1+z} \frac{dz'}{1+z'} \frac{n_{HI}(z')\sigma_{\rm ion}\left(\epsilon_0 m_{27.2}\frac{1+z'}{1+z}\right)c}{H(z')}. \tag{5}$$

If we take Eq. (4) for n_{HI}, the integral becomes trivial and

$$P(z) = \left(\frac{1+z}{1+z_i}\right)^3 \tag{6}$$

where the epoch of ionization is defined as

$$1+z_i = 16\left[\frac{m_{27.2}^{3/2}-1}{\alpha_{3000}\tau_{24}\ln(m_{27.2})}\right]^{1/3} \tag{7}$$

The probability that a photon gets absorbed goes to one as z approaches z_i from below; z_i is therefore the epoch at which most hydrogen became ionized. Since z_i is so large for typical values of τ, $P(z)$ is small throughout all epochs probed by Gunn-Peterson tests [which are, of course, at z much less than 16]; therefore, corrections to Eq. (4) are correspondingly small.

Figure 1 (solid line) shows the bounds on m_ν and τ coming from the strictest Gunn-Peterson test [presently at $z = 4.1$] [11]. The upper limit on the lifetime is determined by requiring that $n_{HI}(z = 4.1)$ is less than the observed upper bound. Note that even for lifetimes larger than this upper bound, the Universe may still be almost completely ionized; it is the "small" remnant level of n_{HI} due to recombinations that come into conflict with observations.

Photon Spectrum. Measurement of the diffuse photon flux, I_0, can also be used to constrain and ultimately test the DDM scenario.

The photon flux today due to the decaying neutrinos is $I_0 = (c/4\pi)E dn_\gamma/dE$. dn_γ/dE is given in Eq. (2), but we must modify this expression to account for damping. The damping factor, though, is simply $e^{-P(z_E)}$, where $P(z_E)$ is the probability [calculated in Eq. (6)] that a photon emitted at $1 + z_E$ will be absorbed, and z_E is the epoch at which a photon with energy E today was emitted. Clearly, $1 + z_E = (m_\nu/2)/E$, so the photon flux today is

$$I_0 = \frac{8.5 \times 10^4}{\tau_{24} h} \left(\frac{E}{(m_\nu/2)}\right)^{3/2} \exp\left\{-\frac{([m_\nu/2]/(1+z_i))^3}{E^3}\right\} \mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{sr}^{-1}. \qquad (8)$$

This expression holds only as long as Eqs. (4) and (6) are valid; that is, as long as $E > (m_\nu/2)/(1+z_i)$, For $E < (m_\nu/2)/(1+z_i)$, corresponding to photons created while the universe was still opaque, the flux is essentially zero, as all of these photons were absorbed by neutral hydrogen atoms.

This prediction of the DDM scenario is most directly confronted by observation of the diffuse UV background. In Figure 2, we plot the predicted photon spectrum today for 3 sets of parameters. Although the spectrum has been calculated numerically [10], the analytical expressions discussed here are accurate approximations of the exact results. Many groups have attempted to measure the UV background [12]; the data points in Figure 2 are upper limits on the extragalactic component of the measured flux from some recent observations. There is some disagreement both on the data and its interpretation among the various groups. Hurwitz *et al.* [12] concluded that most of the background can be attributed to galactic processes, predominantly scattering by dust. Their upper limits on the extragalactic componenet are the most restrictive and were used in Fig. 1 (dashed line). At the other extreme, Murthy *et al.* [12] find no correlation with Galactic variables; the upper limits from their data are accordingly much less restrictive and have also been included in Fig. 1 (dotted line). The former limits leave open only a small region of parameter space and rule out Sciama's preferred values of $m_\nu = 28.9 \pm 1.1$eV and $\tau = 2 \pm 1 \times 10^{23}$sec. The latter limits do not exclude these values, but even modest improvements in the limits would rule them out. Data from the Astro-1 mission [13] and from IUE [14] may have already done so, though one cannot discount the possibility of absorption by a cloud of gas along the line of sight. We would like to stress however that even if these results are taken at face value, they rule out only masses smaller than 32.1eV and lifetime less than 3×10^{23}sec. Gunn-Peterson data still allow a larger parameter space, which can be tested by improved measurements of the diffuse UV background.

The peculiar signature of the DDM scenario is evident in the infrared (IR) portion of the spectrum. It is in this region that the effects of reionization can be observed. In Figure 3 we have plotted the predicted photon flux in the IR. If neutrino decay were the only source of photons, the IR spectrum would have a sharp cutoff at $(m_\nu/2)/(1+z_i)$. Aside from the decay photons, however, it is necessary to include the Lyα photons, as well. Recombination to excited states results in electrons which cascade down to the $2p$ state

to the ground state with the emission of a Lyα photon, at $\epsilon_\alpha \equiv 10.2$eV. (We have ignored the relatively small contribution of photons which decay by two photon emission from the $2s$ state.) At energies between $\epsilon_\alpha/(1+z_i)$ and $(m_\nu/2)/(1+z_i)$, the Lyα radiation provides the dominant contribution. The net result is that there are two pronounced spikes in the spectrum: at $(m_\nu/2)/(1+z_i)$ and at $\epsilon_\alpha/(1+z_i)$. For the Gunn-Peterson allowed parameter space, these bumps occur in the $1-3$ micron range. Unfortunately, this is a notoriously difficult band in which to do astronomical observations because of the redness of the night sky. The current upper limits on the IR background are provided by DIRBE [15] and are several orders of magnitude away. However, with improved modelling to discriminate the true extragalactic background from galactic sources, these limits should be greatly reduced over the next few years.

In conclusion, we have analyzed the DDM solution to the reionization problem and calculated its obervable predictions, the remnant neutral hydrogen density and the diffuse photon flux, as a function of the two unfixed parameters of the theory: the mass and lifetime of the decaying particle. Improved data from Gunn-Peterson tests and from observations of the photon background are converging to test the allowed parameter space.

Acknowledgements

We would like to thank B. Barnes, E. Bertschinger, K. Freese, P. Schechter, and A. Stebbins for useful discussions. The work of SD was supported in part by DOE and by NASA under Grant No. NAGW-2381 at Fermilab. JJ acknowledges the Sloan Foundation under Grant No. NSF PHY-9296020 for partial support.

References

[1] C. C. Steidel and W. L. W. Sargent, *Astroph. J.* **318**, L11 (1987).

[2] D. W. Sciama, *Mon. Not. Roy. As. Soc.* **198**, 1P (1982) ; *Mon. Not. Roy. As. Soc.* **200**, 13P (1982); Y. Rephaeli and A. S. Szalay, *Phys. Lett.* **106B**, 73 (1981); A. L. Melott, *Sov. Astron.* **28**, 478 (1984).

[3] S. S. Gershtein and Ya. B. Zel'dovich, *JETP Letters* **4**, 174 (1966); R. Cowsick and J. McClelland, *Phys. Rev. Lett.* **29**, 669 (1972); G. Marx and A. Szalay in *Neutrino '72*, eds. A. Frenkel and G. Marx (OMDKT-Technoinform, Budapest, 1972), p. 123. General cosmological constraints on neutrino properties are reviewed in K. Freese and D. N. Schramm, *Nucl. Phys.B* **233**, 167 (1984).

[4] We do not consider here the case of very heavy (> GeV) neutrinos.

[5] This follows from requiring the age of the Universe to be greater than 10 billion years. See S. A. Bludman, CfPA-TH-91-004 (1991) for a recent discussion emphasizing the relevance of the age measurements to the neutrino mass upper limit. Allowing a slightly lower age ($\sim$ 8 billion) raises the upper limit on the mass and significantly changes the physics because helium is then also ionized in decays. J. Miralda-Escudé and J. P. Ostriker, *Princeton* POP-415 have recently presented arguments indicating ionization of helium.

[6] D. W. Sciama, *Phys. Rev. Lett.* **65**, 2839 (1990); *Nature* **346**, 40 (1990); *ibid.* **348**, 617 (1990); *Mon. Not. Roy. As. Soc.* **244** 1P (1990); *ibid.* **246**, 191 (1990); *Astroph. J.* **364**, 549 (1990); P. Salucci and D. W. Sciama, *Mon. Not. Roy. As. Soc.* **244**, 9P (1990); D. W. Sciama and P. Salucci, *Mon. Not. Roy. As. Soc.* **247**, 506 (1990). See also A. L. Melott, D. W. McKay, and J. P. Ralston, *Astroph. J.* **324**, L43 (1988)

[7] See, for example, A. P. Lightman and G. B. Rybicki, *Radiative Processes in Astrophysics* (Wiley-Interscience, New York, 1979), chapter 10.

[8] T. P. Walker, G. Steigman, D. N. Schramm, K.A. Olive and H. Kang, *Ohio State University Preprint* OSU-10/90 (1991).

[9] See, for example, F. W. Stecker, *Phys. Rev. Lett.* **44**, 1237 (1980); A. De Rujula and S. L. Glashow, *Phys. Rev. Lett.* **45**, 942 (1980); J. Bernstein and S. Dodelson, *Phys. Rev. D* **41**, 354 (1990).

[10] S. Dodelson and J. M. Jubas, *Fermilab- Pub* 91/260-A. See also D. Scott, M. J. Rees and D. W. Sciama, *Cambridge Astronomy Preprint* (1991); A. Melott and R. Splinter, *Univ. of Kansas preprint.*

[11] J. K. Webb, *et al.*, *ESO Messenger* **51**, 15 (1988). Recently discovered higher redshift quasars have larger upper limits on the optical depth; accordingly the limits on n_{HI} are less severe. See D.P. Schneider, M. Schmidt, and J.E. Gunn, *Astron. J.* **98**, 1507 (1989),and *ibid.* **102**, 837 (1991).

[12] The data used in the figure are taken from: M. Hurwitz, S. Bowyer, and C. Martin, *Astroph. J.* **372**, 167 (1991), C. S. Weller, *ibid.* **268**, 899 (1983), and J. Murthy, R.C. Henry, P.D. Feldman, and P.D. Tennyson, *ibid.* **336**, 954 (1989). For an up to date review, see S. Bowyer, *Annu. Rev. Astron. Astrophys.* **29**, 59 (1991).

[13] A. F. Davidsen *et al.* *Nature* **351**, 128 (1991)

[14] A. C. Fabian, T. Naylor, and D. W. Sciama, *MNRAS* **249**, 21P (1991).

[15] M.G. Hauser *et al.* in *AIP Conference Proceedings* **222**, eds. S.S. Holt, C. L. Bennett, and V. Trimble (American Institute of Physics, New York, 1991), p. 161.

Figure Captions

1. The allowed values of m_ν and τ in the DDM scenario. The solid line represents the *upper* limit on τ coming from Gunn-Peterson tests. The dashed and dotted lines are *lower* limits on τ from observations of the diffuse UV background. Region A is allowed by all UV observations. Region B is allowed by a less restrictive set of observations. See text for discussion.

2. Today's UV flux predicted in the DDM scenario as a function of wavelength for 3 sets of parameters: Sciama's preferred values of $m_\nu = 28.9$eV and $\tau = 2 \times 10^{23}$sec (solid line), $m_\nu = 32$eV and $\tau = 6 \times 10^{23}$sec (dotted line), and $m_\nu = 35$eV and $\tau = 2 \times 10^{23}$sec (dashed line). The data points are observational upper limits on the extragalactic component of the UV background.

3. Today's IR flux predicted in the DDM scenario as a function of wavelength for the same parameters as in Figure 2. The current obervational upper limits are still a few orders of magnitude above prediction, but new COBE data should bring these limits down.

FIGURE 1

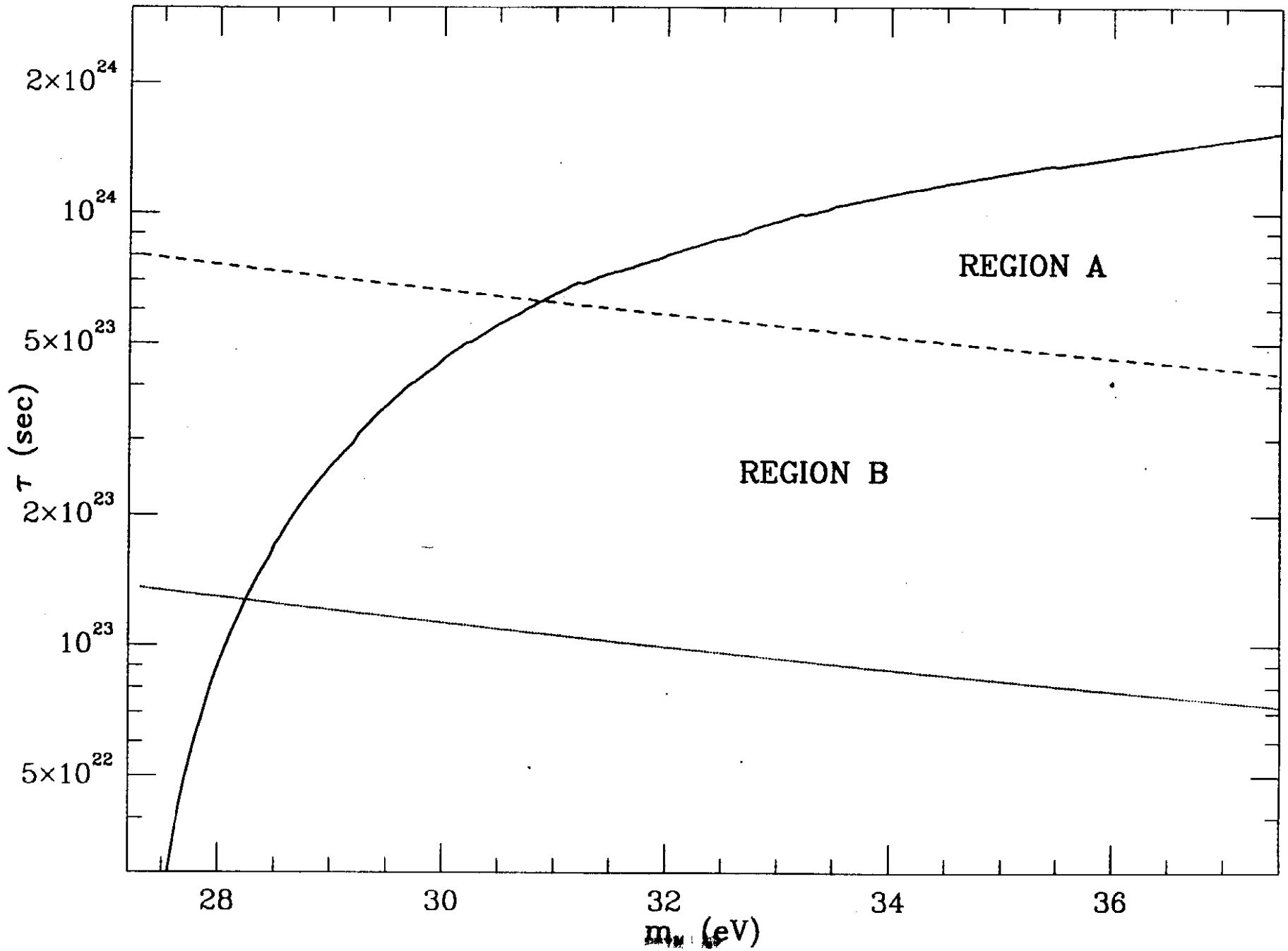

2×10^24
10^24
5×10^23
2×10^23
10^23
5×10^22
τ (sec)
REGION A
REGION B
28
30
32
34
36
m_ν (eV)

FIGURE 2

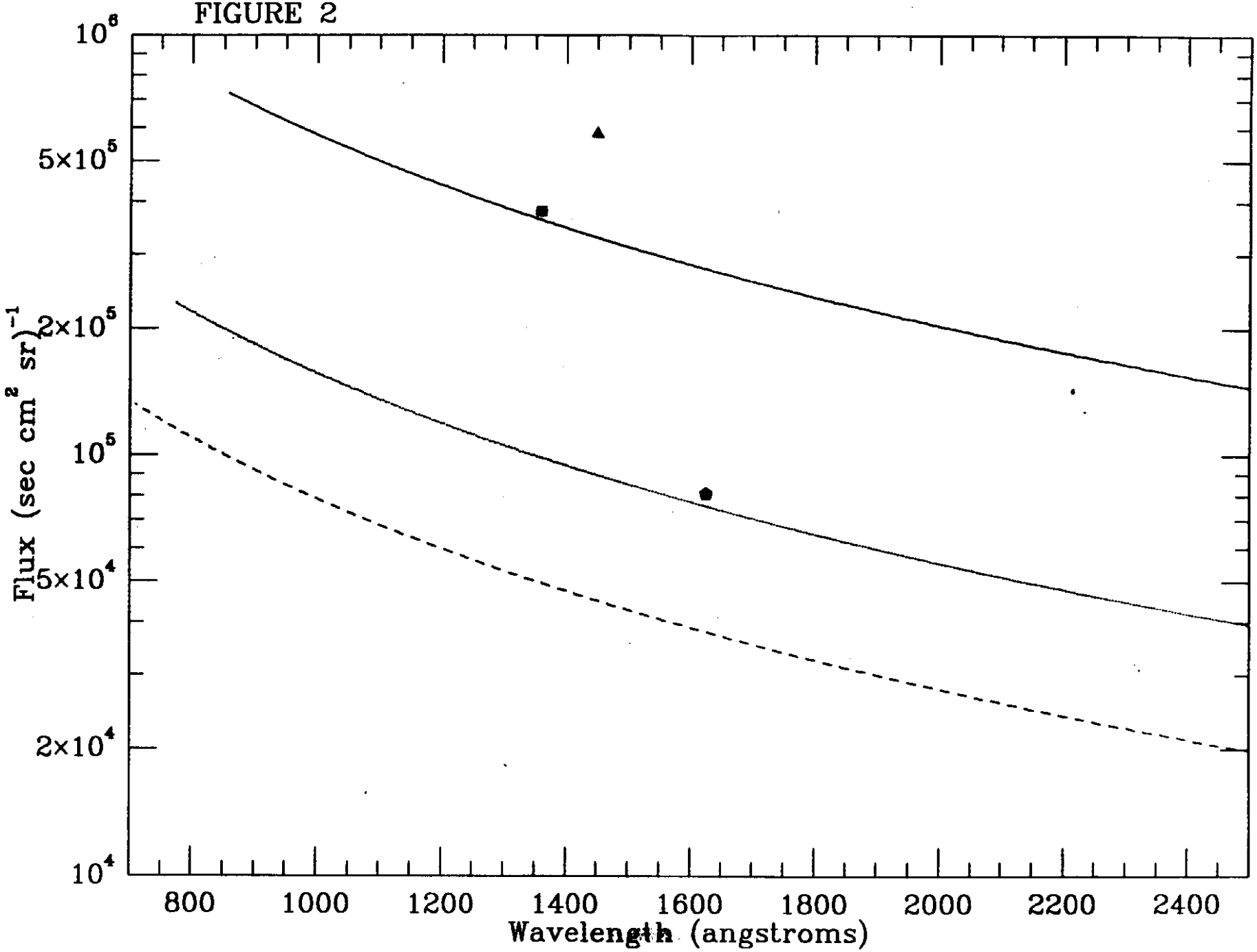
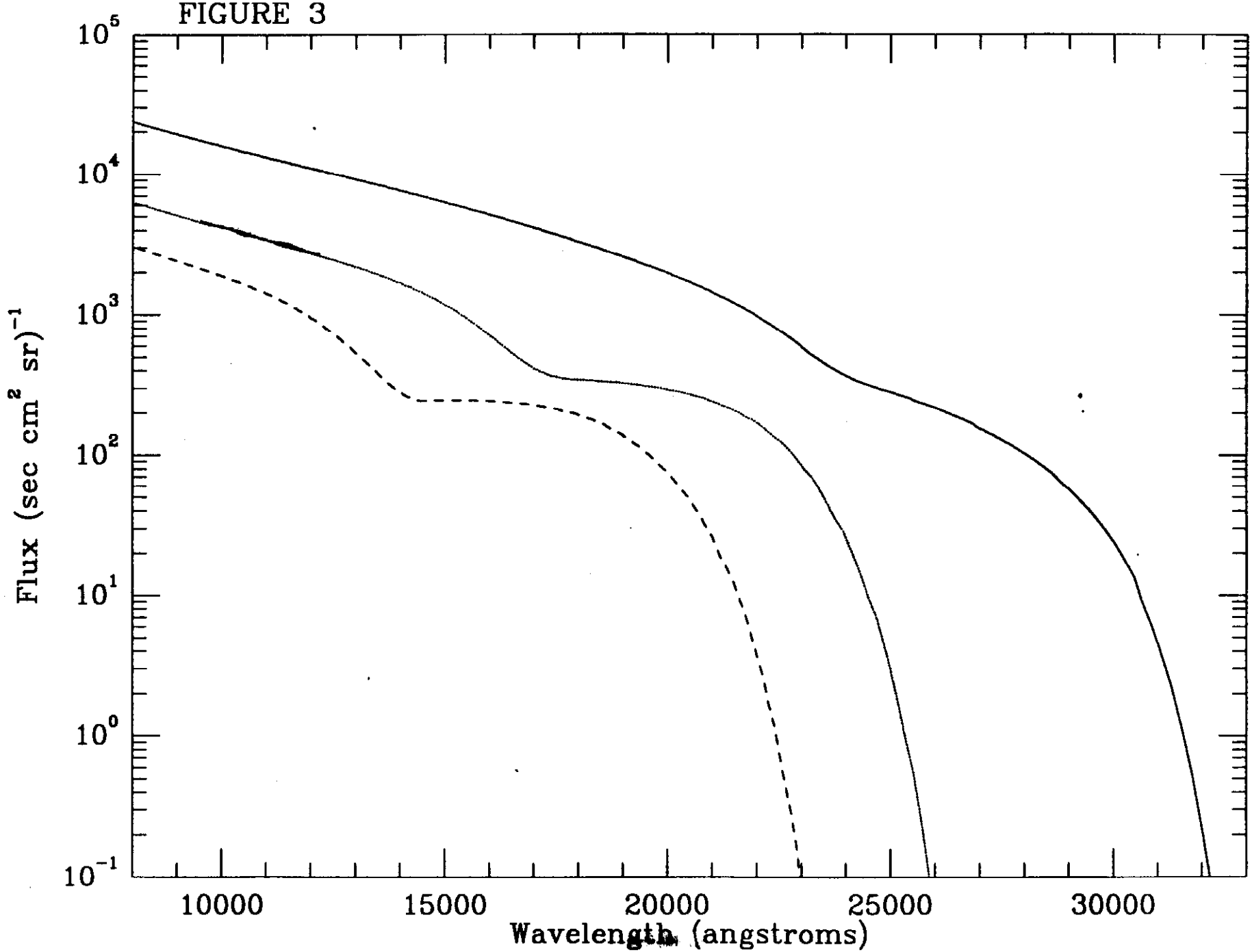

10^6
5×10^5
2×10^5
10^5
5×10^4
2×10^4
10^4
Flux (sec cm^2 sr)$^{-1}$
800
1000
1200
1400
1600
1800
2000
2200
2400
Wavelength (angstroms)

FIGURE 3


10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
Flux (sec cm^2 sr)$^{-1}$
10000
15000
20000
25000
30000
Wavelength (angstroms)