

POSSIBILITY THAT THE FAR ULTRAVIOLET  
EXCESS IN M31 IS DUE TO MAIN SEQUENCE STARS

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ABSTRACT

The far ultraviolet excess in the central region of M31, observed by OAO-2, could be due to young main sequence stars. More than enough such stars are present in the model for the M31 inner disk population derived by Tinsley and Spinrad (1971) to match line- and color-indices at longer wavelengths. If the far ultraviolet radiation of typical galaxies arises from young stars, the theoretical ultraviolet background is enhanced greatly by evolutionary effects. For evolution at the rate of Tinsley and Spinrad's model for M31, or of Arnett's (1971) "linear" model for our galaxy, the enhancement is a factor 2.5 to 14, depending on the Hubble constant and the spectrum at wavelengths below 1700 Å.

I. INTRODUCTION

Hills (1971) has suggested that the far ultraviolet excess in the central region of M31, observed by OAO-2 (Code, 1969), is due to hot, highly evolved stars such as are found in globular clusters. Here, hot, young, main sequence stars are suggested as an alternative stellar source, on the basis of a model by Tinsley and Spinrad (1971) for the inner disk population of M31.

Scanner and filter studies of line strengths (Spinrad et al., 1971) indicate that the stars in M31 in the region covered by the OAO-2 "nuclear" measurement (1800 pc diameter) have predominantly Population I abundances. This fact argues in favor of the present suggestion rather than Hills'. How-

ever, since the model used here is based on detailed line strengths in a region only 200 pc south of the M31 nucleus, and since the angular resolution of the OAO-2 observations is insufficient to show if the ultraviolet excess is confined to much closer to the nucleus, the present suggestion is merely tentative.

## II. THEORETICAL AND OBSERVED FLUX AT 1700 Å

The population model considered, called model D1, is an evolutionary model containing stars formed continuously at a rate depending on stellar mass according to

$$dN/dm \propto m^{-2.5} . \quad (1)$$

Equation (1) holds for stars more massive than 0.14 solar masses, which are the only stars of interest here; further details are given by Tinsley and Spinrad (1971). The stellar birthrate is also proportional to the mass of gas, which changes roughly exponentially with time; over the past two billion years the function is closely represented by

$$m_g(\tau) = m_g(0) e^{\tau/T} , \quad (2)$$

where  $\tau$  = time ago, and  $T = 2.28 \times 10^9$  year. This birthrate gives a synthetic galaxy at age  $12 \times 10^9$  years ( $\tau=0$ ) which has narrow-band line indices closely matching those observed (Spinrad et al., 1971) in the inner disk of M31, and broad-band colors close to those observed (Spinrad et al., 1971; Sandage et al., 1969) from 0.36 to 3.4 micron.

The ultraviolet luminosity of the model at age  $12 \times 10^9$  years, for comparison with M31, can be obtained at wavelength 1700 Å using the stellar data presented by Code (1970) and kindly made available to the author. These data show that the stellar flux at 1700 Å, corrected for interstellar extinction, is given approximately by

$$M(1700 - V) = -0.82 + 11.2(B-V), \quad -0.3 < B-V < +0.5 . \quad (3)$$

It will be assumed here that this relation holds also for redder stars; these contribute negligibly at 1700 Å so that the assumption is of no importance.

The resulting ultraviolet flux for model D1 at  $12 \times 10^9$  years is related to that at the effective wavelength of the U filter band (3600 Å) by

$$F_{1700} / F_U = 0.34 , \quad \text{model D1,} \quad (4)$$

where the U, V magnitudes have been reduced to absolute units using the calibration given by Johnson (1966).

The observed ratio for the inner 1800 pc-diameter region of M31, obtained by interpolation between filter photometer measurements (Code, 1970), is

$$F_{1700} / F_{3600} = 0.09, \quad \text{observed M31.} \quad (5)$$

The latter ratio can be corrected approximately for extinction in the local galaxy by adopting, for M31,  $E(B-V) = 0.11$ ,  $E(U-V) = 0.2$ , and from Figure 7 of Code (1969),  $E(1700-V) \sim 4.5 E(B-V)$ . Hence,

$$(F_{1700} / F_{3600})_c \sim 0.12, \quad \text{observed M31.} \quad (6)$$

Extinction within M31 may require further correction upwards in the observed ratio.

No attempt will be made here to follow Hills in synthesizing a detailed spectrum from below the Lyman limit to 5000 Å, because of the large and uncertain effects of interstellar extinction on the spectral shape.

### III. DISCUSSION

Model D1 is about three times as bright in the far ultraviolet, relative to 3600 Å, as the observed region of M31, according to equations (4) and (6). Because of the considerable uncertainties in the interstellar extinction (local and in M31), and in the preliminary observations available here, the factor 3 discrepancy is not serious. Of chief interest is the fact that at least enough far ultraviolet light to account for the observed excess can arise from young main sequence stars, present in proportions already suggested by a study of line and color indices at longer wavelengths.

### IV. IMPLICATIONS FOR THE BACKGROUND RADIATION

If the far ultraviolet excess in M31 and other galaxies arises from young stars, the theoretical ultraviolet background radiation will be increased by evolutionary effects, because of the greater number of such stars in the past. This effect will be illustrated here by finding the effect on the theoretical background intensity at 1700 Å of galactic evolution at the rate of model D1 for the M31 inner disk, and at the rate of the "linear" model of Arnett (1971) for our galaxy. The latter may be more representative of the "average" galaxy contributing to the background.

Since the stars contributing most of the far ultraviolet light have lifetimes much less than the time-scale of evolu-

tion of a galaxy, it can be assumed that the ultraviolet luminosity of a galaxy is proportional to the stellar birthrate, which in both models considered is proportional to the mass of gas. This is given by equation (2), with  $T = 2.28 \times 10^9$  year for model D1, and  $T = 3 \times 10^9$  year for Arnett's model.

It is a standard result that for cosmological models with zero cosmological constant ( $\Lambda$ ), the background intensity at 1700 Å is given by

$$I_{1700} = \frac{n_0 c}{4\pi H_0} \int_0^{z_{\max}} \frac{L_\lambda(\lambda, \tau) dz}{(1+z)^4 (1+2q_0 z)^{1/2}} \text{ ergs sec}^{-1} \text{ cm}^{-2} \text{ ster}^{-1} \text{ \AA}^{-1} \quad (7)$$

where  $z$  is the redshift;  $\lambda$  is the wavelength of emission,  $\lambda = 1700 \text{ \AA} / (1+z)$ ;  $L_\lambda(\lambda, \tau)$  is the luminosity of a galaxy at wavelength  $\lambda$  and past time  $\tau$ , in units  $\text{ergs sec}^{-1} \text{ \AA}^{-1}$ ;  $H_0$  is the Hubble constant, in  $\text{sec}^{-1}$ ;  $n_0$  is the local number density of galaxies, in  $\text{cm}^{-3}$ ;  $q_0$  is the cosmological deceleration parameter.

The available preliminary OAO-2 observations do not establish the spectral index below 1700 Å accurately, so two extreme alternatives will be considered here, with the true spectrum probably lying between them:

$$L_\lambda(\lambda, \tau) = L_\lambda(1700, \tau) e^{b(1700 - \lambda)/1700}, \quad 912 \text{ \AA} \leq \lambda \leq 1700 \text{ \AA} \quad (8)$$

where  $b = 3$  or zero. Also it will be assumed that

$$L_\lambda(\lambda, \tau) = 0, \quad \lambda < 912 \text{ \AA} . \quad (9)$$

Therefore the upper limit to the integral in (7) is  $z_{\max} = 1700/912 - 1 = 0.863$ . Assumption (9) means that the lowest possible limit to the contribution to the background from greater redshifts is used.

The integral will depend to some extent on  $q_0$ , but not critically since  $z_{\max}$  is not large. The mathematically simplest case,  $q_0 = 0$ , will be used; this behaves very similarly to the cosmological model with Oort density ( $\sigma_0 = q_0 = 0.015$ ). In this case,

$$\tau = t_0 \left(1 - \frac{1}{1+z}\right), \quad t_0 = H_0^{-1}, \quad (10)$$

where  $t_0$  is the age of the universe. Introducing equations (8) to (10), with (2) for the time-dependence of  $L_\lambda(\lambda, \tau)$ , into (7), gives

$$I_{1700} = \frac{n_0 c L_{1700}}{4\pi H_0} \int_0^{0.464 t_0} (1-\tau/t_0)^2 e^{(a+b)\tau/t_0} d\tau/t_0, \quad (11)$$

where  $L_{1700} \equiv L_\lambda(1700,0)$ , and  $a = t_0/T$ . The value of  $a$  depends on  $H_0$  and the evolutionary model, as shown in Table 1. Also tabulated are the values of  $\tau(z_{\max}) = 0.464 t_0$ . The values of  $H_0$  chosen for illustration are  $50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ , as one of the lowest values commonly used, and  $80 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ , as the largest value consistent with model D1, which requires  $t_0 \geq 12 \times 10^9 \text{ year}$ . The factor before the integral in equation (11) is independent of  $H_0$  if the same distance scale is used in determining  $n_0$  ( $\propto \text{distance}^{-3}$ ) and  $L_{1700}$  ( $\propto \text{distance}^2$ ).

Table 1. Parameters for calculation of the background intensity

$H_0$ (km sec <sup>-1</sup> Mpc <sup>-1</sup> )	80	50
a in model D1	5.30	8.56
a in Arnett's model	4.1	6.5
$\tau(z_{\max})$ (10 <sup>9</sup> years)	5.6	9.1

The results of analytical integration of equation (11) are given in Table 2, for the illustrative values of  $b$  and  $H_0$  and the two evolutionary models. Evolutionary effects are found to enhance the theoretical far ultraviolet background due to stars by a factor 2.5 to 13.6. Similar values would be obtained with other values of  $q_0$  in cosmological models with  $\Lambda = 0$ , and the larger values in long-lived models with  $\Lambda > 0$ . Uncertainties in the spectrum below 1700 Å and in the Hubble constant are more important. The two evolutionary models give similar results, which lends some weight to the effects found here since the rate of evolution in Arnett's model was derived from considerations entirely independent of those used in deriving model D1. Also, the relative theoretical intensity of the background with and without evolutionary effects is not affected by the discrepancy between D1 and the observed far ultraviolet luminosity of M31, noted in §III.

Table 2. Normalized background intensity at

$$1700 \text{ \AA}, \left( \frac{4\pi H_0}{n_0 c L_{1700}} \right) I_{1700}$$

Spectral parameter	b=3		b=0	
	$H_0$ (km sec <sup>-1</sup> Mpc <sup>-1</sup> )	80	50	80
No evolution	0.53	0.53	0.28	0.28
Model D1	2.37	7.26	0.97	2.58
Arnett's model	1.62	3.03	0.70	1.36

If the hypothesis of this paper is correct, that the far ultraviolet excess observed in M31 and other galaxies is due to young main sequence stars, evolutionary enhancement of the theoretical ultraviolet background will place severe constraints on possible cosmological models, since Code (1970) has shown that even without such enhancement some models are ruled out by this test. These constraints will be evaluated when further observational data on the ultraviolet background intensity are available.

I am very grateful to Dr. A. D. Code for making some graphical data from OAO-2 available to me prior to its publication, after his presentation at the Texas Symposium on Relativistic Astrophysics in Austin, Texas, December 1970.

This work was partially supported by NSF Grant GP-30455X and by a Grant-in-Aid from Sigma Delta Epsilon.

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