A model for the continuum energy distribution of the ultraluminous galaxy IRAS F10214+4724

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ABSTRACT

If indeed early type galaxies used up most of their gas to form stars in a time short compared to their collapse time and if a roughly constant fraction of metals is locked up in dust grains, these galaxies may easily become opaque to starlight and emit most of their luminosity in the far-IR. The corresponding spectral energy distribution matches remarkably well the observed continuum spectrum of the ultraluminous galaxy IRAS F10214 + 4724 from UV to sub-mm wavelengths, i.e. over almost four decades in frequency, for a galactic age $\gtrsim 1$ Gyr. The bolometric luminosity in this model is $\sim 2.7 \times 10^{14} L_\odot (H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}, \Omega = 1)$, i.e. somewhat lower than implied by previous models. In the present framework, the bolometric luminosity of the galaxy is expected to decrease by a factor $\gtrsim 30$ during the subsequent evolution.

Key words: galaxies: evolution – galaxies: individual: IRAS F10214+4724 – galaxies: elliptical – infrared: galaxies

1 INTRODUCTION

Optical searches for protogalaxies and, in general, for high redshifts galaxies have been remarkably unsuccessful, in spite of many years of efforts (Djorgovski, Thompson, & Smith 1993; Cowie, Scangula, & Hu 1991; Colless et al. 1993), while a couple of apparently genuine young galaxies have been discovered in samples selected at longer wavelengths, i.e. in the radio (53W002, at $z = 2.390$; Windhorst et al. 1991) and in the far-IR (IRAS F10214 + 4724 at $z = 2.287$; Rowan-Robinson et al. 1991). An additional actively star forming galaxy at $z \sim 2$ may have been detected as a damped Ly$\alpha$ absorber (Elston et al. 1991). In view of this fact and of the difficulties facing the alternative merging scenario, at least as far as bright galaxies are concerned (see Franceschini et al. 1993), it is worthwhile to investigate the possible effect of dust on the optical visibility of early phases of galaxy evolution (van den Berg 1990; Wang 1991; Kormendy & Sanders 1992).

Mazzie et al. (1992, 1993) have worked out models for the broad band photometric evolution of disk and spheroidal galaxies from UV to millimetric wavelengths, taking into account in a self consistent way the chemical evolution of the interstellar medium, the evolution of the dust content, the corresponding extinction and reradiation by dust, under the assumption that galaxies were closed systems. Broadly speaking, disk galaxies correspond to the case of a slow gas depletion, i.e. of a star formation rate (SFR) never much higher than it is today, while spheroidal galaxies are thought to have used up most of their gas to form stars in a time short compared to the collapse time, so that their SFR should have been initially very high (Sandage 1986). Thus, the spectral energy distribution of disk galaxies should not have varied much during most of their lifetime; on the contrary, spheroidal galaxies are expected to have been much brighter in their early evolutionary phases. If the early metal enrichment was fast enough, and the dust to gas ratio is roughly proportional to the metallicity, the galaxy may easily become optically thick during these early gas rich, very high luminosity phases.

Franceschini et al. (1993) have investigated implications of these models for deep optical, near-IR, far-IR and radio counts of galaxies and for the corresponding redshift distributions, to conclude that models implying an opaque early phase in the evolution of spheroidal galaxies can account both for the lack of high redshift galaxies in deep optical surveys and for the deep $60\mu$m IRAS counts and also for a good fraction of sub-mJy radio sources detected in VLA surveys.

In this paper, we compare the continuum spectral energy distribution predicted by such models with observational data on IRAS F10214 + 4724, the putative protogalaxy for which the most extensive spectral coverage is presently available (Rowan-Robinson et al. 1991; Soifer et al. 1991; Clements et al. 1992; Downes et al. 1992; Lawrence et al. 1993). In the general framework described above, the observational evidence that this galaxy is undergoing a giant starburst on the scale of the whole galaxy suggests that it is a proto-elliptical galaxy (van den Berg 1990; Elbaz et al. 1992). In Section 2 we will then describe the key features of our evolutionary models for spheroidal galaxies. In Section 3 we will compare model predictions with observational data and discuss some implications. In Section 4 we outline the main conclusions. Throughout this paper we use $H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$ and $\Omega = 1$.

2 THE PHOTOMETRIC EVOLUTION MODEL

Our evolutionary synthesis model is described by Mazzei et al. (1993). Here we recall only the basic ingredients.

The unreddened stellar energy distribution from UV to mid-IR (N band) was obtained as follows. The number of stars born at each galactic age and the gas metallicity were computed by solving the standard equations governing chemical evolution. Schmidt’s (1959) parametrization ($\psi(t) = \psi_0 f_g(t)^n m_{\odot} \text{yr}^{-1}$ where $f_g$ is the gas fraction) has been adopted for the star formation rate (SFR). As for the initial mass function (IMF), we have considered both a Scalo’s (1986) and a Salpeter’s (1955) form; in the latter case, different choices for the lower mass limit have been explored. The isochrones by Bertelli et al. (1990), extended by Mazzei (1988), have been exploited to get the distribution of stars of each generation in the H-R diagram.
Dust extinction was estimated assuming a spherically symmetric King’s (1966) distribution of well mixed stars, gas and dust. The dust to gas ratio was taken to be proportional to the gas metallicity \( Z_g \). The optical depth is thus proportional to \( f_g(t)Z_g(t) \) and increases rapidly with decreasing galactic age. In our baseline model we adopt the coefficient of proportionality determined by Mazzei et al. (1993) from their analysis of a sample of local early type galaxies. We have also employed the slightly more elaborate model proposed by Guiderdoni & Rocca-Volmerange (1987) whereby the dust to gas ratio is proportional to \( Z_g^a \) with \( s = 1.6 \) for \( \lambda > 2000 \text{ Å} \) and \( s = 1.35 \) at shorter wavelengths; the results are basically similar. The standard mean extinction curve for the interstellar medium in our own Galaxy (Seaton 1979; Rieke & Lebofsky 1985) was adopted.

The starlight absorbed by dust is reemitted in the far-IR. Its spectral distribution was modelled following Xu & De Zotti (1989), i.e. taking into account the contributions of two components: warm dust, located in regions of high radiation field intensity (i.e. in the neighborhood of OB associations), and cold dust, heated by the general interstellar radiation field. The warm to cold dust radiation intensity was taken to be proportional to the star formation rate, as described in Mazzei et al. (1993). Given the extreme star formation activity of IRAS F10214 + 4724, the warm dust component is strongly dominant.

Emission from circumstellar dust shells around OH/IR stars was also taken into account. The total luminosity of such stars at each galactic age is taken to be 5% of the global luminosity of AGB stars with initial masses in the appropriate range.

3 RESULTS AND DISCUSSION

If indeed a roughly constant fraction of metals present at any time is locked into dust grains, the dust extinction in spheroidal galaxies is bound to be large during the early evolutionary phases when a substantial metal enriched interstellar medium was present. If the gas metallicity increases fast enough, the galaxy becomes opaque during the first 1 or 2 Gyrs of its life, so that most of the luminosity comes out at far-IR wavelengths, as observed for IRAS F10214 + 4724.

An example, corresponding to a power law index \( n = 0.5 \) for the SFR and to a Salpeter’s IMF, is shown in Fig. 1. A very good fit of the data is obtained for a galactic age \( T \approx 1 \text{ Gyr} \), implying a redshift of formation \( z_f \approx 4 \). The SFR at this age is \( 3 \times 10^4 M_\odot \text{ yr}^{-1} \) and the average extinction is \( A_B \approx 4.6 \text{ mag} \). This model has significantly less power in the IR than the best fit model by Rowan-Robinson et al. (1993; their model B) and, correspondingly, a significantly lower bolometric luminosity \( L_{\text{bol}} \approx 2.7 \times 10^{14} L_\odot \).

The metallicity is predicted to be roughly solar, consistent with the (still uncertain) observational indications (Downes et al. 1992; see, however, Brown & Vanden Bout 1992 for a significantly lower estimate).

Figure 1 illustrates the photometric evolution predicted by the model, showing that the far-IR to optical luminosity ratio decreases very fast with increasing galactic age, reaching the very low values typical of present early type galaxies at an age of \( \sim 15 \text{ Gyr} \).

It must be stressed that, in this general framework, the age of the best fit model is not unambiguously determined. Quite generally, however, we may conclude that it is unlikely to be substantially higher than \( T = 1 \text{ Gyr} \). This is because the luminosity of the UV branch decreases as stellar populations get older making increasingly difficult to account for the observed UV flux in the presence of the strong absorption required to explain the far-IR.

On the other hand, it is possible to obtain a fit comparable to that in Fig. 1 assuming a lower galactic age (see, for example, Fig. 2). As shown by Fig. 1, the model gets bluer at earlier times. Thus a simple recipe to obtain a fit with a lower \( T \) is to assume a higher absorption during the earliest evolutionary phases; as a result, the metallicity associated to the best fit model decreases, if the other model parameters are kept unchanged.

Obviously, the metallicity at a given galactic age is higher and higher as the IMF is more and more weighted towards massive stars. The requirement that it does not exceed the solar value then implies relatively low galactic ages. For example, in the case of a Scalo’s (1986) IMF, a solar metallicity is reached at \( T = 0.4 \text{ Gyr} \) and in the case of a Salpeter’s (1955) IMF with a lower mass limit \( m_l = 0.5 M_\odot \) at \( T = 0.1 \text{ Gyr} \). The faster increase of the metallicity naturally provides the stronger extinction required to compensate for the more intense UV branch; only minor adjustments of the optical depth are needed to get a good fit (see Fig. 2).

The total mass of the model galaxy also critically depends on the IMF. A standard Salpeter’s (1955) IMF with a lower mass limit \( m_l = 0.01 M_\odot \) implies a total mass of \( \approx 5 \times 10^{13} M_\odot \). This estimate however may need a substantial downward correction if indeed formation of low mass stars is inhibited in starbursts. Increasing the lower mass limit to \( 0.5 M_\odot \) would translate in a decrease of the estimated total mass to \( \approx 7 \times 10^{12} M_\odot \).

It may be noted that a galactic age of 1 Gyr corresponds to the characteristic timescale for gas consumption in elliptical galaxies; the subsequent evolution is then be characterized by a rapid dimming (cf. Fig. 3) amounting to a factor of more than 30 by the present time. Thus, IRAS F10214+4724 could be the progenitor of a \( z = 0 \) elliptical galaxy with a bolometric luminosity of \( \lesssim 10^{14} L_\odot \).

4 CONCLUSIONS
Under the very simple assumption that the dust to gas ratio in galaxies is always roughly proportional to the metallicity of the interstellar medium, early type galaxies are expected to undergo an opaque phase during their early evolution whenever the metal enrichment is sufficiently rapid. We have shown that the ensuing spectral energy distribution for a galactic age of $\lesssim 1\,\text{Gyr}$ matches impressively well the observational data for the ultraluminous IRAS F10214+4724 over almost four decades in wavelength, i.e. from UV to sub-mm, without any need of invoking additional contributions from e.g. an active nucleus and assuming the standard mean extinction curve for our own Galaxy.

While this galaxy is extraordinary as far as the luminosity is concerned, it may well be that an optically thick early phase, corresponding to the maximum bolometric luminosity, is a common property of early type galaxies. As discussed by Franceschini et al. (1993), a photometric evolution of this kind would simultaneously explain the lack of high redshift galaxies in optically selected samples down to $B = 25$ and the 60$\mu$m counts of galaxies in the deep IRAS survey.

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FIGURE CAPTIONS

Fig. 1. Spectral energy distribution for several galactic ages for a Salpeter’s IMF with a lower mass limit \( m_l = 0.01 \, m_\odot \), a star formation rate proportional to \( f_0^{0.5} \) (see Sect. 2) and a gas to dust ratio proportional to metallicity (\( s = 1 \)). Data are from Rowan-Robinson et al. (1993) and Downes et al. (1992). The best fit corresponds to a galactic age, \( T \), equal to 1 Gyr.

Fig. 2. Spectral energy distribution at galactic ages of 0.1–0.4 Gyr for the same model as in Fig. 1, except for a larger lower mass limit (\( m_l = 0.5 \, m_\odot \)); also, the coefficient of proportionality for the optical depth (see Sect. 2) has been increased by a factor 1.5.

Fig. 3. Bolometric luminosity of our baseline model as a function of galactic age, assuming \( \Omega = 1 \) (see text).