On the Effects of Bursts of Massive Star Formation During the Evolution of Elliptical Galaxies

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ABSTRACT

We consider the hypothesis that the formation of elliptical galaxies includes a phase in which star formation is mostly restricted to massive stars, with the bias towards high mass stars increasing with elliptical galaxy mass. The mass fraction of stars in this top-heavy mode of star formation is constrained by requiring the resulting stellar remnants to account for the observed increase in the mass-to-light ratio of ellipticals with increasing galaxy mass. We then consider the implications of this population of massive stars for the intracluster medium and the extragalactic background at various wavelengths. The mass and abundance ratios of metals produced by our proposed population of massive stars are consistent with the observations of the mass and abundance ratios of metals in the hot gas of galaxy clusters for most of the standard range of IMF slopes and SN II yields. The predicted energy density produced by this stellar population approaches current limits on the extragalactic background at both optical wavelengths, into which the ultraviolet radiation of the massive stars is likely to be redshifted, and far-infrared wavelengths, at which starlight reprocessed by dust associated with the starburst will be observed. In either case, the background is predicted to be significantly clustered since massive ellipticals are clustered.

Subject headings: galaxies: formation - galaxies: ellipticals and lenticular, cD - galaxies: starburst - X-ray: galaxy clusters - cosmology: diffuse radiation

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1. Introduction

One of the remarkable features of elliptical galaxies is the very narrow dispersion in the relationship between effective radius, surface brightness within that radius, and the central velocity dispersion (Dressler et al. 1987, Djorgovski & Davis 1987). This “Fundamental Plane” of elliptical galaxies can be written as

\[ R_e \propto \sigma^A \Sigma^B_e, \]

where, in the B band, the exponents A and B are 1.3 and −0.8 respectively with about a 10% uncertainty. The deviation of this relationship from a purely virial one leads to the scaling between mass-to-light ratio and mass, \((M/L)_B \propto M^{0.2}\) (Faber et al. 1987). More recently, near-infrared studies have shown that the Fundamental Plane in the K band yields \((M/L)_K \propto M^{0.16}\) (Pahre, Djorgovski, & de Carvalho 1995, Mobasher et al. 1996).

The question arises as to the nature of the physical mechanism driving the scaling between \(M/L\) and \(M\). One potential candidate is metallicity, since metallicity is believed to increase with elliptical galaxy mass/luminosity ratio, and increasing metallicity leads to increasing \(M/L\) in optical bandpasses. However, the effect of metallicity variations on the observed \(M/L\) trend is strongly limited by the observation that the scaling between \(M/L\) and \(M\) extends into the K-band, because according to stellar models \((M/L)_K\) is insensitive to metallicity for old stellar populations. This result is in agreement with earlier work which showed that the change in metallicity inferred from the slope of the color-magnitude relationship leads to \(M/L\) changes that are much less than observed (Dressler et al. 1987). As a specific example, we estimate the increase of metallicity with luminosity from the observed \(K, V - K\) relationship and the models of Charlot & Bruzual (1996). These models suggest metallicity variations affect the the exponent of the scaling between \(M/L\) and \(M\) by less than several-hundredths in the K band.

A second possibility is that the ages of ellipticals may vary systematically with galaxy mass/luminosity. In order to obtain the correct sense of the \(M/L\) trend, low luminosity ellipticals must be much younger than high luminosity ellipticals. We find that variations in the mean stellar age of ellipticals such that the V-K differences are matched can account for about 1/2 of the observed \((M/L)\) scaling. The resulting ages range from about 6.5 Gyr for \(\sim 0.1L_\ast\) ellipticals to about 17 Gyr for \(\sim 3L_\ast\) ellipticals. Such large age differences seem hard to reconcile with the small rms scatter in \((U - V)\) colors for the same ellipticals (e.g. less than 0.04 m in Coma, according to Bower, Lucey & Ellis 1992). Unless the epoch at which star formation terminated was remarkably well coordinated, age variations at a level significant for the \(M/L\) scaling would appear to be ruled out. A finely adjusted combination of age and metallicity might somewhat weaken this constraint.

Another alternative is that the structure of elliptical galaxies may vary with luminosity. This can lead to inferred mass-to-light variations when the mass is derived from the central velocity dispersion and elliptical galaxies are assumed to be homologous. One possibility is that the change from rotational support to velocity anisotropy with elliptical galaxy luminosity may affect the
inferred mass-to-light ratios (e.g. Prugniel & Simien 1994), although other studies have found that the effect on the Fundamental Plane is small (e.g. Djorgovski & Santiago 1993). Alternatively, the density profiles of elliptical galaxies may vary with luminosity (e.g. Caon, Capaccioli, & D'Onofrio 1993), possibly leading to some effect on the scaling of M/L with M (see also Capelato, de Carvalho, & Carlberg 1995). A variation on this overall theme which appeals to changing the radial distribution of cold dark matter halos as a function of elliptical galaxy luminosity was proposed by Guzmán, Bower, & Lucey (1993).

Systematic variations of the stellar initial mass function (IMF) can also produce a trend of M/L with M (e.g. Djorgovski 1988). Most earlier work concentrated on increasing M/L for more massive/luminous ellipticals by tying up more mass in stars well below the main-sequence turn-off through a steeper IMF (Djorgovski & Santiago 1993, Renzini & Ciotti 1993). However, such an IMF leads to stellar abundance trends opposite to those observed, which indicate preferential enrichment from the products of massive stars in the most massive ellipticals (e.g. Worthey, Faber, & Gonzalez 1992, Matteucci 1994). An alternative, first suggested in this context by Larson (1986), is a bimodal IMF, with stellar remnants from an earlier generation of massive stars as an explanation for the increase of M/L with M.

In this paper, motivated by other considerations, we further develop the idea that a bimodal IMF, with stellar remnants contributing significantly to the mass, is responsible for the increase of both M/L and metallicity with increasing galaxy mass. Our hypothesis is that the increase of M/L with M derived from the analysis of the Fundamental Plane is the result of a population of remnants of massive stars which makes up a systematically larger fraction of the mass of the galaxy with increasing galaxy mass, and that the associated supernova ejecta are responsible for explaining an outstanding problem that is closely associated with the presence of early-type galaxies, namely the enrichment of the intracluster medium. We associate the episode of formation of the massive star population with major starbursts, most likely induced as the result of early galaxy mergers which may play an important role in elliptical galaxy formation.

There are both observational and theoretical grounds for the proposal that the initial mass function (IMF) in starbursts is strongly biased towards massive stars. Observationally, several studies of the central regions of starbursts have suggested that the IMF is strongly biased towards high-mass stars (e.g. Rieke et al. 1980, Doane & Mathews 1993, Rieke et al. 1993, Doyon, Joseph, & Wright 1994). From the theoretical standpoint, it has been argued that such an IMF biased towards massive stars is expected in starbursts, especially when a merger is involved. In such a situation, the turbulence in the interstellar medium is much higher than in the Galactic regions for which standard IMFs have been determined, and may play a central role in modifying the IMF (Silk 1995). This effect is likely to be strongest in the starbursts which are the progenitors of the most massive ellipticals, and which have the deepest potential wells.

There is also a variety of circumstantial evidence suggesting that physical conditions during periods of star formation in elliptical galaxies were dependent on galaxy mass. These include
observations of nearby ellipticals which show that [Mg/Fe] increases above the solar value with increasing galaxy luminosity (Worthey et al. 1992, Davies, Sadler, & Peletier 1993), and of distant galaxies with unusually red colors or strong 4000 Å breaks (Charlot et al. 1994). These results are suggestive of an IMF that once was weighted towards massive stars, perhaps during the early merger that was the hallmark of a forming elliptical. Also, the specific frequency of globular clusters increases with elliptical galaxy luminosity (Djorgovski & Santiago 1992; Zepf, Geisler, & Ashman 1994), and may be indicative of a systematic change in the way stars form with increasing potential well depth. Formation of globular clusters does indeed appear to be a signature of major mergers (e.g. Whitmore & Schweizer 1995, Zepf et al. 1996).

A top-heavy IMF during the initial stage of elliptical galaxy formation has also been proposed as a way to account for the large iron masses in galaxy clusters (e.g. Elbaz, Arnaud, & Vangioni-Flam 1995). Recent observations of the elemental abundances of the intracluster gas point to type II SN as the source of enrichment, providing strong support for models with a top-heavy IMF during the formation of elliptical galaxies (Loewenstein & Mushotzky 1996). We will return to the issue of the enrichment of the ICM in Section 3.

The primary goal of this paper is to test the hypothesis that the trend of higher $M/L$ with increasing $L$ is the result of compact stellar remnants from a past burst of formation of high-mass stars in massive ellipticals. Our approach is to fix the remnant population to match the Fundamental Plane results, and then consider the observational implications of the massive star population required to produce these remnants. We note that our focus is on the slope of the Fundamental Plane, and not on its narrowness. A study of the small scatter about the fundamental plane, which implies a high degree of synchronization at any given elliptical galaxy mass/luminosity (e.g. Renzini & Ciotti 1993, Djorgovski & Santiago 1993), is beyond the scope of this paper.

Fortunately, our proposed top-heavy mode of star formation during the evolution of giant elliptical galaxies produces a number of phenomena accessible to observations. One of the most direct tests of the model is the metal yields of the massive star population. We particularly concentrate on the predicted metallicity and abundances of the intracluster medium, for which new data exist. A second test of the model is its contribution to the extragalactic background light at a variety of wavelengths. We find that the model is consistent with the observations, and that the effects of the proposed stellar population may have been observed. We then describe further observational tests of the initial hypothesis. The paper is laid out such that the basic properties of the proposed population are calculated in § 2, comparisons to current observations are given in § 3, and § 4 contains the discussion of future observational tests of our hypothesis.

2. Analysis
Our procedure is to first calculate the mass in remnants required at each elliptical galaxy luminosity in order to explain the observed $M/L$ trend. We then integrate over the luminosity function for early-type galaxies to obtain the global mass density of these remnants. Finally, we use models of stellar populations to predict the metal yields produced by the massive stars which result in the calculated mass in remnants.

In order to determine the fraction of galaxy mass in remnants of massive stars as a function of luminosity, we adopt a fiducial elliptical galaxy luminosity for which all of the stars form with a standard IMF. One natural choice for this luminosity is the point at which the surface brightness–absolute magnitude relationship changes slope, indicating a shift from the population of normal, giant ellipticals to the separate population of dwarf ellipticals (Kormendy & Djorgovski 1989 and references therein). This shift takes place at roughly $M_B = -17 + 5 \log h$, or about 0.1 $L_\star$. We take this to be the luminosity of an elliptical with a “normal” stellar population, and any increase in M/L for more luminous ellipticals to be the result of stellar remnants. The choice of 0.1 $L_\star$ is not a firm one, both because the luminosity of the shift from giant to dwarf ellipticals is not tightly constrained (e.g. Sandage & Perlmutter 1991) and because other effects may play a role in the relationship between $M/L$ and $M$. For example, if we used the shift from dynamical support primarily through rotation as the defining point for an elliptical galaxy with a “normal” stellar population, the luminosity would be a factor of a few higher than 0.1 $L_\star$, albeit with large uncertainties. Similarly, the elliptical galaxy sequence may extend to luminosities fainter than 0.1 $L_\star$. Therefore, we also consider the effect of defining the luminosity at which an elliptical has a “normal” stellar population as 0.03 $L_\star$ or 0.3 $L_\star$. We will refer to a fiducial luminosity of 0.1 $L_\star$ as case one, and these latter two luminosities as cases two and three respectively.

For the $(M/L)_B$ of early-type galaxies at $L_\star$, we adopt $13h$. This is an average of the observed values, which range from 11.9h (van der Marel 1991), 12.7h (Bender, Burstein, & Faber 1992), and 14.5h (Lauer 1985), where these have all been converted to values at $L_\star$. With $(M/L) \propto L^{0.2}$, these values give $(M/L)_B = 8.2h$ at 0.1$L_\star$, and $(M/L)_B = 15.6h$ at 2.5$L_\star$, which is roughly the luminosity of M87. Thus, for case 1 in which ellipticals at 0.1 $L_\star$ have only “normal” stellar populations, about one-third of the mass in ellipticals at $L_\star$ is in remnants of massive stars, and this fraction is almost one-half for ellipticals like M87. For cases 2 and 3, in which 0.03 $L_\star$ and 0.3 $L_\star$ galaxies are “normal”, the fraction of mass in remnants of massive stars is about 60% and 33% respectively for ellipticals like M87. Figure 1 shows graphically how changes in the lower luminosity limit lead to changes in the mass fraction of remnants as a function of luminosity.

For the luminosity function of early-type galaxies, we adopt the usual Schechter form (Schechter 1976) with $L_\star = 1.0 \times 10^{10} h^{-2} L_\odot$ (in the $B$ band), $\alpha = -0.3$, and $\phi_\star = 1.0 \times 10^{-2} h^3$ Mpc$^{-3}$. This luminosity function is based primarily on the recent results of the Las Campanas Redshift Survey (LCRS) for galaxies without emission lines (Lin et al. 1995). Our adopted luminosity function is also similar to that found in the APM-Stromlo survey for galaxies classified morphologically as early-type (Loveday et al. 1992). The differences between the two surveys are relatively minor for our purposes, with Loveday et al. finding a slightly more positive $\alpha$, brighter
$L_\ast$, and smaller $\phi_\ast$ such that the overall luminosity density is very similar. A somewhat different luminosity function for early-type galaxies was derived from the shallower CfA redshift survey by Marzke et al. (1994). They found $\alpha = -0.9$, and a density normalization about a factor of two higher than the other two surveys. We will consider the effects of adopting these latter values for the luminosity function, although the significantly greater volume of the former two surveys suggests that they are more likely to adequately sample the true luminosity function of ellipticals at the present epoch.

To calculate the total mass fraction of the population of the remnants of massive stars, we convolve the mass estimates with the luminosity function for early-type galaxies. The resulting mass function of remnants is shown in Figure 2. This figure also shows the effect of adopting cases 2 and 3 for the cutoff luminosity for elliptical galaxies. For all cases, the dominant contributors to the remnant mass function are elliptical galaxies with luminosities of about $2L_\ast$.

The total mass density of the remnant population is the integral of the mass function shown in Figure 2. For the fiducial case, this density of remnants from the episode of massive star formation which produced the $M/L$ vs. $M$ dependence of elliptical galaxies is $3.7 \times 10^8 h^2 M_\odot$ Mpc$^{-3}$. If we change the cutoff luminosity for elliptical galaxies, the densities are 170% and 40% of the fiducial density, for cases 2 and 3 respectively. Also, if we change the luminosity function to one like that of Marzke et al. (1994), we find that the remnant density is very similar to that given by the fiducial values. The reason for this result is that the remnant density is decreased by the more negative $\alpha$, but increased by a similar amount by the higher normalization. For the remainder of the paper, we adopt a global remnant mass density of $3.7 \times 10^8 h^2 M_\odot$ Mpc$^{-3}$, and assume this value is uncertain by about a factor of two.

The next step is to estimate the yield of metals from the burst of massive stars which produced this density of remnants. This requires the IMF of the starburst, and the metal yield and remnant mass as a function of the stellar mass. For the IMF of the starburst, we rely on observations of starburst galaxies at the current epoch, which suggest that the IMF in these regions may have a lower cutoff at about $3 \ M_\odot$ (e.g. Rieke et al. 1993). On this basis, we adopt an IMF with a Salpeter slope ($x = 1.35$), $m_L = 3 \ M_\odot$ and $m_U = 60 \ M_\odot$. We also consider how variations in the IMF affect the conclusions. In Figure 3, we plot these IMFs and a Miller-Scalo (1986) IMF representing the normal elliptical galaxy population for comparison. We note that the minimum requirement for the IMF of the starburst is that it is restricted to masses greater than about $1 \ M_\odot$ so that these stars are not luminous today.

For the yield of metals from these massive stars, we use the recent Woosley & Weaver (1995) determinations for SN II of various masses. For simplicity, we take the average of their different models for stars of $M \geq 30 \ M_\odot$. The differences between different physical models for these very massive stars produce different net yields of about 20% for the IMFs we consider. The models of Thielemann, Nomoto, & Hashimoto (1995) also produce net yields with differences of this order or somewhat greater. The Thielemann et al. models produce more Mg and less Fe for higher mass
stars than the Woosley & Weaver models.

We track the elements Fe, Mg, and O, as these are the most readily observed in the stars of elliptical galaxies and the hot gas in clusters of galaxies. For O, we also consider the yields from stars with $M < 10 M_\odot$ using the yields of Renzini & Violi (1981). The final ingredient required are the final remnant masses produced, for which we use the values of Prantzos et al. (1993). For massive stars, these are similar to those expected from the Woosley & Weaver models.

The result for our fiducial IMF is that, per solar mass of remnants, a total mass in metals of about $4.2 \times 10^{-1} M_\odot$ is produced, with specific element production of $1.3 \times 10^{-2} M_\odot$ of Fe, $9.9 \times 10^{-3} M_\odot$ of Mg, and $2.2 \times 10^{-1} M_\odot$ of O. These values can then be multiplied by the mass density of remnants for cases 1 and 2 derived above to obtain the global mass density of various elements. Flatter IMFs produce more metals with increases in $[O/Fe]$ and $[Mg/Fe]$; steeper IMFs produce fewer metals with a somewhat lower $[Mg/Fe]$ and $[O/Fe]$ ratios. Raising the upper mass limit increases the yields of O and Mg slightly, and lowering it decreases them slightly. Lowering the lower mass limit decreases the yields of O and Mg and also Fe slightly, whereas raising it primarily increases the overall yield, as long as $M_{low} < M_{SNII}$. Use of the Miller-Scalo IMF, peaking near $0.3 M_\odot$ but with a flatter IMF slope above $1 M_\odot$ would provide an alternative to a truncated IMF for the starburst, but at the price of enhancing the SN I/SN II rate and thereby reducing the yield for a given $M/L$ value.

3. Observational Implications

3.1. Metal Production

Accounting for the metals produced by this burst of high-mass star formation is a critical test of the model. This test is straightforward in the sense that the model makes specific predictions about the masses of various metals and which galaxies produce them. Moreover, it is expected that a starburst will drive a strong galactic wind, particularly when predominantly high mass stars are formed (e.g. Doane & Mathews 1993). This expectation is supported by observations of “superwinds” driven by starbursts (e.g. Heckman, Armus, & Miley 1990). To first order, most of the metals produced will end up in the intergalactic medium (IGM), or in the case of cluster galaxies, the intracluster medium (ICM). The real situation is undoubtedly more complex, involving the interplay of structure evolution, gravitational interactions, star formation, hydrodynamics, and chemical evolution. However, a useful starting point is the comparison between the metals produced in the proposed burst, and those observed in the IGM or ICM.

The comparison with the ICM is particularly interesting, because abundances can be derived from X-ray observations of hot gas in clusters, and because these regions are rich in early-type
galaxies. As a specific example, we consider the well-studied Coma Cluster. For Coma, the overall luminosity is $L_B = 1.9 \times 10^{12} \, h^{-2} \, L_\odot$ (e.g. Godwin & Peach 1977, Kent & Gunn 1982). Taking this luminosity, accounting for the contribution of galaxies other than early-types, and plugging in to our previous values for the mass of remnants and Fe at a given number density of early-type galaxies, we find a mass in remnants of $M_{rem} \approx 5.9 \times 10^{12} \, h^{-1} \, M_\odot$ and a Fe mass of $M_{Fe} \approx 7.7 \times 10^{10} \, h^{-1} \, M_\odot$. For the mass in Fe inside an Abell radius, we convolve the White et al. (1993) estimate of the gas mass $M_{gas} \approx 5.45 \times 10^{13} \, h^{-5/2} \, M_\odot$ in Coma with its Fe abundance, which is about 0.35 solar (Ohashi 1995) and find $M_{Fe} \approx 2.3 \times 10^{10} \, h^{-5/2} \, M_\odot$. Thus given the assumption that all of the metals produced by the burst of massive stars are ejected into the ICM, our fiducial case predicts an Fe mass in Coma which is $3.4 h^{3/2}$ greater than that observed.

This comparison is shown graphically in Figure 4, in which we plot the predicted $M_{Fe}$ as a function of the luminosity at which an elliptical galaxy is fixed to have a “normal” stellar population. The plot demonstrates that the model with the fiducial values is a reasonable fit to the data if $h$ is close to 0.5, and requires a somewhat brighter cutoff luminosity for ellipticals if $h$ is closer to 1.0. An alternative approach is to follow Arnaud et al. (1992) and Renzini et al. (1993) and adopt a typical “iron mass to light ratio (IMLR).” These authors show that observed IMLR values are roughly $M_{Fe}/L_{E/S} = 0.02 h^{-1/2}$. For our fiducial values, we find that this ratio is 0.039 $h$.

We note that these calculations are based on the assumption that all of the metals from the burst of massive stars are ejected into the ICM. This probably represents an upper limit to the metals contributed to the ICM, since some of the metals are likely to be locked up in generations of “normal” star formation which occur at the same time or after the phase of massive star formation. The supersolar values of $[\text{Mg/Fe}]$ observed in massive ellipticals are indicative of enrichment from an episode of massive star formation (e.g. Worthey et al. 1992, Matteucci 1994). We can roughly estimate the amount of mass in metals locked up in this way by requiring that all of the “excess” Mg observed in the stars of ellipticals originated in the burst of massive stars. This represents about half of the total metal production of the massive star formation phase. Thus the above predictions for the model production of Fe are reduced by about a factor of two.

We find that the best prediction of our fiducial model is that it produces an Fe mass of 1-2 $h^{3/2}$ times the observed Fe mass in clusters. This agreement is very promising, and well within the uncertainties of the calculation. These uncertainties include the luminosity function of early-type galaxies, the slope and limits of the top-heavy IMF, the yields from SN II, the adopted ratio $M_{Fe}/L_{E/S}^{E/S}$, which is higher given a radially increasing gas to luminous mass ratio and lower with a declining radial gradient in metallicity, as well as the luminosity at which elliptical galaxies have “normal” stellar populations. We conclude that the fiducial model successfully predicts the Fe mass in galaxy clusters, and look for other observational tests.

The abundance ratios of various elements provide a powerful test of theories for the enrichment of the ICM. The prediction of our fiducial model is fairly simple; the abundance ratios should
be like the yields from type II SN. Recent ASCA data for four clusters find almost exactly such abundance ratios (Mushotzky et al. 1996). Thus the X-ray determined abundance ratios favor SN II as the source of the enrichment of the ICM, independently of any specific model (Loewenstein & Mushotzky 1996). The strength of our model is that it naturally accounts for both the total Fe mass and the abundance ratios in the ICM, given only the constraint that the modified IMF accounts for the $M/L$ trend of elliptical galaxies in terms of compact remnants of massive stars.

Massive elliptical galaxies are not located solely in rich clusters, so the IGM will also be enriched by massive ellipticals in poor clusters and groups. Most of the ejecta are unlikely to be retained by galaxy groups, and will become part of the diffuse IGM. The observational constraints on the metal content of the IGM are few. However, we note that the global enrichment is expected to be substantial. Given our fiducial model and the adopted luminosity function for early-type galaxies, the mass density of metals is $1.6 \times 10^8 h^2 M_\odot Mpc^{-3}$. About half of this mass is likely to have been ejected from galaxies, leading to an inferred enrichment of the IGM, $Z_{IGM}/Z_\odot \approx 0.01 \Omega_{IGM}^{-1}$.

### 3.2. Extragalactic Background Light

We have shown that a starburst composed of high mass stars constrained to account for the change in $M/L$ with $L$ observed in elliptical galaxies produces metal abundances in general agreement with that observed in the ICM. Another implication of such a burst is its effect on the extragalactic background light, as the energy density produced by the large numbers of high mass stars may be significant. The energy density of a population of stars can be written as a function of the metal density it produces,

$$\nu_i = \epsilon c^2 (\rho Z) c / 4\pi (1 + z_f)^{-1},$$

where $z_f$ is the redshift at which the starburst occurs, and the value of $\epsilon$ is about 0.004 for stars in the mass range of interest (Bond, Arnett, & Carr 1984). This calculation is straightforward for our model, because we have previously found the mass density of metals to be $1.6 \times 10^8 h^2 M_\odot Mpc^{-3}$, or $(\rho Z) = 1.1 \times 10^{-32} h^2 g cm^{-3}$ in more conventional units for this type of work. The resulting energy density is then $\nu_i = 86 (1 + z_f)^{-1} h^2 nW sr^{-1}$. For canonical values of $z_f$ of about 3, this is $22 h^2 nW sr^{-1}$.

Most of the energy of massive stars is radiated in the ultraviolet. If these massive starbursts typically occur at moderately high redshift, and there is little dust, this energy density will be seen as a diffuse optical extragalactic background. The observational limit on the background at 4000 Å is $20 nW sr^{-1}$ (Mattila 1990). As shown in Figure 5, the prediction of the fiducial model is somewhat lower than these upper limits for typical values of $h$. There is also reason to believe that the burst of massive star formation may be dust-shrouded. There are close analogies between this
phase of elliptical galaxy formation and ultraluminous starbursts: the rate and efficiency of star formation are comparable, and the luminosity profiles of merger products, in the post-starburst phase, appear to be evolving towards $r^{1/4}$ profiles (e.g. Schweizer 1990, Wright et al. 1990). Moreover, while the mild evolution observed for ellipticals in clusters at $z \sim 0.4$ argues for the formation of the bulk of the stars at $z \gtrsim 2$, (e.g. Ellis 1996, Bender et al. 1995), unsuccessful searches for luminous forming galaxies to $z \sim 5$ (Pahre & Djorgovski 1995) may be accounted for if protoellipticals are dusty.

If the burst of massive star formation is shrouded in dust, the ultraviolet radiation from massive stars will be reprocessed into the far-infrared. The radiation density of local starbursts peaks at about $60\mu$, which for typical formation redshifts, would be detected at present at roughly $240\mu$. The DIRBE instrument on the COBE satellite is sensitive to diffuse backgrounds at these wavelengths. Hauser (1995) gives an upper limit at $240\mu$ of $\nu i_\nu \leq 20\text{nW sr}^{-1}$, and Puget et al. (1995) argue that a diffuse background is detected in these data at the level of $\nu i_\nu \approx 3 - 10\text{nW sr}^{-1}$ at similar wavelengths. The best constraints on an extragalactic background at longer wavelengths come from the stringent limits on deviations from a blackbody in the FIRAS spectrum of the CMB (Mather et al. 1994). Blain and Longair (1993) consider a number of models, including some whose evolution and metal production are similar to ours, and find consistency with the FIRAS data. However, the results are dependent on the temperature and other physical properties of the dust, and low dust temperatures can raise the predictions above the FIRAS limit.

By analogy with starbursts, it is more likely that the correct model is a mixture of the two cases described above, rather than one in which either all or none of the ultraviolet light is absorbed by dust and reradiated in the far-infrared. The same class of objects would then be responsible for most of the diffuse background at optical and far-infrared wavelengths. A prediction of this scenario is that the cosmic backgrounds in the optical and the far-infrared are correlated with one another. Moreover the spatial structure of both of these backgrounds should reflect the enhanced correlations of ellipticals relative to spirals.

4. Discussion

We have explored the consequences of the hypothesis that remnants of massive stars make up a systematically larger fraction of the masses of elliptical galaxies with increasing galaxy mass such that they account for the scaling $(M/L)_B \propto M^{1/6}$. We find that this hypothesis is in good agreement with observations of metals in clusters and extragalactic background light. In fact, the observations seem to lead in the direction of models such as that explored here. The observational confirmation that the elemental abundances in the hot cluster gas resemble those of SN II is indicative of an early population of massive stars as the source of these metals (Loewenstein & Mushotzky 1996). The suprasolar [Mg/Fe] ratios of massive ellipticals make them attractive
candidates for the location of the stellar population that incorporates some of the ejecta from these massive stars. The increasing mass-to-light ratio with elliptical galaxy mass provides a natural place for the remnants of the massive star population which produced the SN II. There is no unique inference of an IMF, since our constraint is an integral one. However we find it remarkable that to within the uncertainties in the comparisons of about a factor of two, a consistent model can be constructed accounting for all of these observations.

We note that the supernova rate per unit luminosity required by our model of ICM enrichment is enhanced relative to conventional Galactic models by a factor of $\sim 5$, the ratio of $M_{Fe}/M_*$ in clusters to its value in the Milky Way, for which the ratio of SN Ia to SN II that reproduces the observed abundances is approximately 0.15 (Tsujimoto et al. 1995). Since SN Ia leave no compact remnants, our model and the observed abundance ratios require the ICM Fe to be produced almost exclusively by SN II. Hence the rate of SN II in protoellipticals is enhanced by a factor of about 6 relative to the SN II rate requirements of the standard chemical evolution model for the Galaxy. What we have not addressed here in any detail are the means by which the enriched debris is ejected into the ICM and IGM. A galactic wind is likely, and given the high supernova rate may well be inevitable even from massive galaxies. Our model predicts about 0.2 SN II per $M_\odot$ of remnants. We will discuss elsewhere the implications of such a high supernova rate for the interstellar medium in the starburst. This may lead to important consequences for such supernova byproducts as cosmic rays and gamma rays. Although the details are sensitive to the low energy cosmic ray spectrum, it would be of interest to compute the effects of spallation and LiBeB production as well as of gamma rays from nuclear excitations and $\pi^0$ decays arising from cosmic ray interactions with the dense protogalactic interstellar gas.

The formation of the large number of massive stars indicated by our model may have a significant effect on the extragalactic background light. We find that our fiducial model produces an extragalactic background just below the current observational limits. Studies of the extragalactic background at various wavelengths are probably the most promising way to further constrain our hypothesis. One aspect of our model is that the background is expected to be clustered, since most of it is produced by bright elliptical galaxies, which are known to be significantly clustered. This clustering may help distinguish our model from other models, such as a simple luminosity evolution in which all sources become brighter in the past or density evolution in which the number of sources at all luminosities increases (e.g. Lonsdale et al. 1990, Saunders et al. 1990). However “backwards evolution” models like these have an ad hoc normalization which is typically set by requiring that the models not overproduce the cosmic infrared background. Alternatively, models like those of Franceschini et al. (1994) are based on the local luminosity function and a prescription for the star formation history of different galaxy types. The predictions of our models for observations at far-infrared and sub-mm wavelengths are equivalent to a luminosity-dependent density evolution, with the evolution concentrated on the brightest and most clustered objects, and with the normalization fixed by the observed metallicity production.

The bursts of massive star formation may lead to bright sources which are individually
detectable, particularly if the burst occurs on a fairly short timescale. Searches for these discrete sources in the far-infrared and sub-mm are an especially promising possibility. The expected surface density of starbursts associated with the formation of giant ellipticals is roughly

\[ 2000h \left( \frac{t_{sb}}{10^8 \text{yr}} \right) \text{deg}^{-2}, \]

where we have adopted \( z = 3 \) as the burst redshift, and an \( \Omega = 1 \) cosmology. The typical bolometric luminosity is a few \( \times 10^{13} L_\odot \), comparable to that of ultraluminous starburst galaxies and quasars. The predicted flux at 300\( \mu \) is about 10 mJy, given \( z_f = 3 \) and the bolometric correction such that \( L_{60\mu}/L_{bol} \) is a few percent, by analogy with objects such as IRAS F10214+4724. For lower formation redshifts, the fluxes of individual sources are higher, but the surface density is lower. Similarly, the scaling with the starburst timescale is such that the surface densities increase and the individual fluxes decrease with increasing \( t_{sb} \). If ellipticals at the current epoch are the result of subsequent, mostly stellar, mergers of several earlier starbursts, then the predicted surface densities go up by a factor of several and the individual fluxes are reduced by the same factor.

Hence coverage of \( \sim 10 \) square arc-minutes with a deep survey by ISO in the far-infrared, or at submillimeter wavelengths by a bolometer array such as is available at IRAM, CSO or (soon) at JCMT, should lead to detections of the dust-shrouded starbursts that, we have suggested, herald elliptical formation. It is conceivable that quasars are not completely unrelated to our proposed protoelliptical starburst phase. A burst of massive star formation need not preclude the presence of an AGN (Djorgovski 1994), and some models suggest a connection between a massive central starburst and the formation of an active nucleus (e.g. Norman & Scoville 1988). It is an intriguing coincidence that abundance ratios in quasar emission line regions are also indicative of a massive star-dominated nucleosynthetic yield from Type II supernovae (Hamann & Ferland 1993, Matteucci & Padovani 1993).

The model presented here also makes predictions for observational tests of elliptical galaxy evolution. If the \( M/L \) trend of ellipticals is a result of remnants from a burst of massive star formation, the Fundamental Plane of ellipticals is expected to evolve in a way very similar to that of passive evolutionary models, at least until the redshift of the burst is approached. In contrast, models in which the \( M/L \) trend reflects age variations would be expected to show rather rapid changes with redshift in the slope of the Fundamental Plane. Another prediction of the model is that \( M/L \) residuals should correlate with [Mg/Fe] residuals. Furthermore, the small scatter about the Fundamental Plane provides constraints on the evolution of elliptical galaxies. If the mass fraction in the top-heavy mode of star formation is determined solely by the mass of the protoelliptical at the time of the starburst, then variations in the history of subsequent mergers and accretions will introduce scatter about the Fundamental Plane for any given final elliptical galaxy mass. Although dependent on cosmology and the details of the merging process, it is likely that the mass distribution of captured objects will be steeply declining, so that the resulting dispersion need not be excessive. Given the observed dispersion about the Fundamental Plane \( \sigma(M/L)_{B} \lesssim 20\% \), and that our model attributes about one-third of the mass of a typical elliptical to stellar remnants of the merger-induced starburst, a dispersion of up to a factor of 50% in
merged masses is acceptable.

Finally, our model makes predictions for the history of the enrichment of the intrachannel medium. A burst of massive star formation during the formation of elliptical galaxies will lead to early enrichment of the ICM. Thus observations of X-ray gas in moderate and high redshift clusters would be expected to show metallicities which are similar to those in galaxy clusters today, or even higher if infall has diluted the metallicites of rich clusters at low redshift. This prediction is in agreement with the ASCA observation of Abell 370 at $z = 0.37$ (Bautz et al. 1994).

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Figure Captions

Figure 1 - A plot showing the variation of mass-to-light ratio with elliptical galaxy luminosity and the fraction of the total mass in remnants. The upper half of the plot describes the mass-to-light ratio, with the top line being the observed M/L vs. L relationship, and the straight lines representing various choices for the luminosity at which remnants from a phase of high-mass star formation begin to account for the M/L trend. The masses of this population of remnants are simply the difference between the upper curve and the straight lines, and are shown graphically in the lower half of the plot.

Figure 2 - A plot of the mass densities of stellar remnants as a function of elliptical galaxy luminosity. This quantity is a convolution of the remnant masses as a function of galaxy luminosity in Figure 1, with the adopted luminosity function for early-type galaxies. For reference, the elliptical galaxy luminosity function is plotted as a solid line above the others. This plot shows that the dominant contribution of remnant mass (and thus metals and background light) is from ellipticals at about $2 L_\star$. The integral of these curves gives the total mass density of remnants for the various models.

Figure 3 - This plot compares the IMFs considered for the top-heavy starburst with a standard IMF. The top-heavy IMFs are given by the dashed lines, and the normal IMF by the solid line. The various dashed lines correspond to IMFs with a slope of -1, -1.5, and -2. The normalization between the starburst and normal population shown is that for an $L_\star$ elliptical galaxy.

Figure 4 - This plot shows the predicted Fe mass in the Coma cluster as a function of the luminosity at which remnants of the massive stellar population begin to contribute to mass-to-light ratio. The observed value for the Coma cluster is shown as the solid line. The model provides a good fit to the data for the fiducial case and $h$ close to 0.5, or for cutoff luminosity closer to that of case 3 if $h$ is closer to 1.0. Note that this plot overestimates the Fe production of the model because it does not account the metals retained by the ellipticals.

Figure 5 - A plot of the energy density of the extragalactic background light produced by the massive star population, as a function of the elliptical galaxy luminosity at which it begins to come into play. The observed upper limit at 4000 Å is shown as a solid line. This is the same energy density as the upper limit at 240μ given by Hauser (1995). Much like the Fe prediction in Figure 4, the model provides a good fit to the data for low $h$ and the fiducial cutoff luminosity, and requires a somewhat higher cutoff luminosity if $h$ is high.
