SETTING THE STAGE:
ULTRALUMINOUS GALAXIES IN A COSMOLOGICAL CONTEXT

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Abstract

I will try to put the ultraluminous galaxy phenomenon into a broad cosmological context. Viewed from this perspective, the significance of ultraluminous galaxies and the 'starburst vs. monster' debate becomes clear. Ultraluminous galaxies are fascinating in their own right, allow detailed study of the processes by which massive spheroids were built and the IGM was heated and polluted, and resemble the most luminous and dustiest galaxies at high-redshift. Ultraluminous galaxies were apparently far more common at $z \sim 3$ than today. Recent inventories in the local universe of the cumulative effect of nuclear burning (metal production) and of monster-feeding (compact dark objects in galactic nuclei) imply that either stars or monsters could have generated the observed far-IR cosmic background. The starburst vs. monster debate has global, as well as local importance.

1. Introduction

In this introductory talk I will address two questions. First, are ultraluminous galaxies of fundamental significance, or just interesting curiosities? Second, why do we care whether starbursts or monsters dominate the energetics of ultraluminous galaxies? I will argue that the answers to these questions are clear when addressed in a global, cosmological context. In what follows, I will define an ultraluminous galaxy to be a galaxy having a bolometric luminosity exceeding $10^{12} \, L_\odot$ for $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ and a spectral energy distribution that is dominated by rest-frame mid/far infrared emission.
2. Are Ultraluminous Galaxies Important?

2.1. MOTIVATION

We now have a rather complete energetic census of the ‘local’ \((z \leq 0.1)\) universe. Comparing the luminosity functions of far-IR selected galaxies, optically-selected galaxies, and quasars (cf. Soifer et al 1987) implies that ultraluminous IR-selected galaxies are of comparable energetic significance to quasars of similar bolometric luminosities, but are responsible for only of-order 1% of the far-IR emissivity (luminosity per unit co-moving volume element) and \(\sim 0.3\%\) of the total bolometric emissivity in the local universe. Thus, on simple energetic grounds it might indeed be possible to dismiss ultraluminous galaxies as merely intriguing oddities.

The generic response to such a dismissal is to reply that although they are rare, ultraluminous galaxies are excellent local laboratories in which the physics and phenomenology of galaxy building can be studied in far greater detail than at high redshift. Some of the lessons that we have learned from the investigation of local ultraluminous galaxies have potentially wide-ranging implications. These include the role played by galactic mergers in making (some/all?) elliptical galaxies (cf. Schweizer 1997), the apparent efficacy with which such mergers can transport much of the ISM of the merging galaxies into the circumnuclear region (e.g. Mihos & Hernquist 1994), the subsequent triggering of circumnuclear star-formation at a rate approaching the maximum allowed by physical causality (viz. SFR \(\sim M_{\text{gas}}/t_{\text{cross}}\) - Heckman 1993), and the resulting heating and metal-enrichment of the inter-galactic medium by galactic ‘superwinds’ that are driven by the collective effect of the millions of supernovae and stellar winds in the starburst (cf. Heckman et al 1996).

On the other hand, given the current paradigm of the hierarchical assembly of galaxies in which (to quote Simon White) ‘Galaxy formation is a process rather than an event’, it is a fair and certainly germane question to ask whether typical galaxies ever go through an ultraluminous phase. More precisely: could the ultraluminous phenomenon be an integral part of the formation of galactic spheroids (ellipticals and bulges)? Is Arp 220 really a galactic ‘Rosetta Stone’ or just an ‘infra)red herring’?

The recent stunning advances in the observation of galaxies at high redshift mean that we can finally start to answer these questions directly.

2.2. THE LYMAN BREAK GALAXIES AS ULTRALUMINOUS GALAXIES

Dickinson (1998) has recently published an ultraviolet (1500 Å rest-frame) luminosity function for a large sample of galaxies at \(z \sim 3\) from the Hubble Deep Field and larger but shallower ground-based surveys, selected on the
basis of their rest-frame UV spectral energy distributions (the ‘U drop-out’ or ‘Lyman Break’ galaxies). Ignoring any correction for dust extinction, this luminosity function would imply that galaxies with apparent UV luminosities exceeding $10^{12} \, L_\odot$ are exceedingly rare in the early universe, with co-moving space densities of-order $10^{-4}$ that of present-day normal Schechter $L_\star$ galaxies.

Far be it from me to propose at a conference laden with infrared astronomers that we actually ought to ignore the effects of dust on these results! Indeed, the generation of techniques to correct the Lyman Break galaxies for the effects of extinction has evolved into a virtual cottage industry (e.g. Madau, Pozzetti, & Dickinson 1998; Meurer, Heckman, & Calzetti 1999; Pettini et al 1998; Sawicki & Yee 1998). Daniela Calzetti will give a report from the front lines on this issue later in this conference. To summarize, plausible values for the mean/typical UV extinction suffered by the Lyman Break galaxies range from 1 to 4 magnitudes. The UV color-luminosity relation for the Lyman Break galaxies in which the fainter galaxies are bluer (Dickinson, private communication) is reminiscent of the strong dependence of extinction on luminosity seen in local starbursts (Heckman et al 1998). This implies that a correction of the observed UV luminosity function of the Lyman Break galaxies for extinction will change the shape of the function, and not merely its normalization in luminosity. This is clearly seen at low-redshift (Buat & Burgarella 1998).

Meurer, Heckman, & Calzetti (1999) have made a rough attempt to correct the Lyman Break luminosity function at $z \sim 3$ for the effects of luminosity-dependent extinction. Their results imply that galaxies with intrinsic UV luminosities of $10^{12} \, L_\odot$ are actually rather common at $z \sim 3$, with a co-moving space density that is of-order $10^{-1}$ that of present-day Schechter $L_\star$ galaxies. The luminosity/extinction correlation means that the spectral energy distributions of the most luminous Lyman Break galaxies should then be dominated by the infrared, so they would meet my definition of ‘ultraluminous galaxies’. Thus, the co-moving space density of ultraluminous galaxies at $z \sim 3$ would be similar to the space density of M82-level starbursts today.

2.3. THE SCUBA SOURCES IN CONTEXT

ISO and especially SCUBA have opened a new window on the early universe and allowed us to make the first direct comparisons of the far-IR properties of the universe of today to the distant past. The presentation of these marvelous new results will constitute a major portion of this conference, so I will keep my remarks brief.

While the distribution of the SCUBA sources in redshift is still a matter
of on-going investigation (e.g. Lilly et al. 1998; Trentham, Blain, & Goldader 1998; Smail et al. 1998), it is clear that they constitute a major new population of objects that are energetically significant in a cosmological context. As described above, Meurer, Heckman, & Calzetti (1999) have used empirical methods for correcting the Lyman-Break population at $z \sim 3$ for extinction. The extinction-corrected intrinsic UV luminosity function they derive implies that the most luminous Lyman-Break galaxies may overlap the SCUBA sub-mm population in luminosity and space-density.

Heckman et al. (1998) have shown that local starbursts obey quite strong relations between such fundamental parameters as luminosity, metallicity, extinction, and the mass of the galaxy hosting the starburst. More massive galaxies host more metal-rich starbursts, which are in turn more heavily extincted by dust. This probably reflects the well-known mass-metallicity relation for galaxies and the roughly linear dependence of the dust/gas ratio on metallicity. Moreover - and as noted above - the more luminous local starbursts are more heavily extincted by dust, and the UV color-magnitude relation for the Lyman Break galaxies suggests this may also be true at high-redshift.

It therefore seems plausible that the SCUBA sources at high-z are the high-luminosity tail of the Lyman-Break population, and probably represent the most metal-rich (dustiest) starbursts occurring in the most massive halos. This idea is certainly consistent with a strong similarity between the high-z SCUBA sources and local ultraluminous galaxies.

3. Starbursts Versus Monsters: A Global Inventory

Of course, the over-arching theme of this conference is the debate over the nature of the fundamental energy source in ultraluminous galaxies: starburst or monster? In the spirit of the rest of my talk, I’d like to consider the issue of the relative energetic significance of stars vs. monsters from a global perspective. Andy Lawrence develops many of the same themes in his contribution to this conference.

First, we can conduct an inventory of the luminous energy present in the universe today. This represents the cumulative effect of the production of luminous energy over the history of the universe (primarily by stellar nuclear-burning and accretion onto supermassive black holes), diminished only by the $(1+z)$ stretching of the photons. This inventory is made possible by the recent ultra-deep near-UV-through-near-IR galaxy counts in the Hubble Deep Field (Pozzetti et al. 1998) on the one hand, and the landmark detection by COBE of a far-IR/sub-mm cosmic background on the other (Puget et al. 1996; Hauser et al. 1998; Schlegel, Finkbeiner, & Davis 1998).

The total present-day energy density contained in the cosmic IR back-
ground is $\sim 6 \times 10^{-15}$ erg cm$^{-3}$ (Fixsen et al. 1998), which is comparable to the total energy density contained in the NUV-through-NIR light due to faint galaxies (Pozzetti et al. 1998). The origin of the latter is clear: the light of these faint galaxies is overwhelmingly due to ordinary stars (nuclear fusion). However, the origin of the cosmic IR background is not so clear. As I will outline below, simple ‘from-first-principles’ arguments imply that this luminous energy may have been generated predominantly by either stars or monsters that were deeply shrouded in dust.

One obvious way to evaluate whether stellar nucleosynthesis could have been responsible for producing the energy contained in the cosmic IR background is to take an inventory of the byproducts of nuclear burning in the local universe. The recent compilation assembled by Fukugita, Hogan, & Peebles (1998) implies that the baryonic content of galaxies, the intracluster medium, and the general inter-galactic medium is $\Omega_B \sim 4.3 \times 10^{-3}$, $2.6 \times 10^{-3}$, and $1.4 \times 10^{-2}$ respectively. If we adopt a mean metallicity of 1.0, 0.4, and 0.0 $Z_\odot$ for these respective baryonic repositories and use the estimate due to Madau et al. (1996) that each gram of metals produced corresponds to the generation of $2.2 \times 10^{19}$ ergs of luminous energy, the implied co-moving density of energy produced by nuclear burning is then $2 \times 10^{-14}$ erg cm$^{-3}$. If we instead assume that the ratio of metals inside galaxies to those outside galaxies is the same everywhere as it is clusters of galaxies (cf. Renzini 1997), then the total mass of metals today is about twice as large as the above estimate, as is the associated luminous energy. To compare these values to the cosmic IR background, we need to know the mean energy-weighted redshift at which the photons in the IR background originated. Taking $< z > = 1.5$, the resulting observable energy density in the present universe would be in the range 8 to $16 \times 10^{-15}$ erg cm$^{-3}$. This is comparable to the sum of the energy contained in the IR plus the NUV-through-NIR backgrounds. Thus, there is no fundamental energetics problem with a stellar origin for the cosmic IR background.

What about dusty quasars? At first sight, this does not appear to be a plausible source for the bulk of the cosmic IR background. The cumulative emission from the known population of quasars - selected by optical, radio, or X-ray techniques - has resulted in a bolometric energy density today of about $3 \times 10^{-16}$ erg cm$^{-3}$ (cf. Chokshi & Turner 1992), only about 5% of the cosmic IR background. But, what if there exists a substantial population of objects at high-redshift that are powered by accretion onto supermassive black holes, but which are so thoroughly buried in dust that they radiate primarily in the IR, and have thus far been missed in quasar surveys? That is, could the cosmic IR background be produced by a population of monster-powered ultraluminous galaxies at high redshift? Might the SCUBA sources be our first glimpse of this population? Could this same population of dust-
enshrouded AGN be responsible for the bulk of the cosmic hard X-ray background (as Fabian et al. 1998 have argued)?

One way to assess whether accretion onto supermassive black holes is an energetically feasible source for the observed cosmic IR background is to examine the fossil record in nearby galaxies. The generation of the cosmic IR background by the accretion of matter onto supermassive black holes necessarily implies that the centers of galaxies today will contain the direct evidence for this accretion. Is there enough mass in the form of supermassive black holes in galaxies today to have produced the IR background?

Recent dynamical surveys of the nuclei of nearby galaxies suggest that supermassive black holes are common or even ubiquitous, with a mass that is $\sim 0.5\%$ of the stellar mass of the spheroid (bulge or elliptical) within which the black hole resides (Magorrian et al. 1998; Richstone et al. 1998). The corresponding ratio of black hole mass to spheroid blue luminosity in solar units is roughly 0.045 for a Schecter $L_*$ elliptical. Fukugita, Hogan, & Peebles (1998) estimate that the present-day blue luminosity density associated with spheroids is $4.6 \times 10^7 \, L_\odot \, \text{Mpc}^{-3}$, so the implied mean density in the form of supermassive black holes is $\sim 2 \times 10^6 \, M_\odot \, \text{Mpc}^{-3}$.

If we assume that accretion onto a supermassive black hole releases luminous energy with an efficiency $\epsilon = 10\%$ ($E = \epsilon M c^2$), the present-day black hole mass density implies a total production of $1.2 \times 10^{-14} \, \text{erg cm}^{-3}$ in co-moving coordinates. If the energy-weighted mean redshift at which this was emitted is $z \sim 2$, the present-day luminous energy density is then $4 \times 10^{-15} \, \text{erg cm}^{-3}$. This is roughly an order-of-magnitude larger than the luminous energy produced by the known quasar population, but matches the energy contained in the cosmic IR background rather well.

There are therefore three possible interpretations of this. First, we may have substantially over-estimated the mass of black holes in the nuclei of galaxies today. A recent analysis by van der Marel (1999) yields an mean ratio of black-hole-mass to spheroid luminosity that is a factor of 2 to 3 smaller than the Magorrian et al. value. Second, the formation of a supermassive black hole may occur with a mean efficiency for the production of radiant energy that is small (e.g. 1% rather than 10%). Perhaps the quasar phase corresponds to high efficiency and produces most of the radiant energy, but most of the accretion and black hole growth produces very little radiation (e.g. Narayan 1997). Third, maybe the cosmic IR background does have a substantial contribution from dust-enshrouded ‘monsters’. If true, this would imply that over the history of the universe, monsters have produced as much luminous energy as stars!
4. Summary

When examined from a global, cosmological perspective, the answers to the two questions I posed in the Introduction seem clear:

1. **Are ultraluminous galaxies of fundamental significance, or just interesting curiosities?**

   Ultraluminous galaxies are spectacular and fascinating in their own right. They are unique local laboratories that allow the detailed investigation of the physical processes by which galaxies were built and by which the intergalactic medium was heated and chemically-enriched. The most luminous members of the Lyman Break galaxy population at high-redshift are almost certainly ultraluminous systems dominated by far-IR emission and the SCUBA sources at high-z (probably the most metal-rich, dustiest starbursts occurring in the most massive halos) resemble local ultraluminous galaxies. Thus, dusty ultraluminous galaxies have been responsible for a significant fraction of the high-mass star-formation and associated metal production at early times.

2. **Why do we care whether starbursts or monsters dominate the energetics of ultraluminous galaxies?**

   We now know that the cosmic IR background contains as much energy as the integrated UV, visible, and NIR light from all the galaxies in the universe. Recent inventories of the by-products of both nuclear burning (metals and post-big-bang He) and of black hole accretion (dark compact objects in galactic nuclei) in the present-day universe imply that *either* a population of dusty star-forming galaxies *or* of dust-enshrouded monsters could have readily produced the IR background. Thus, on a global scale, the ‘starburst vs. monster’ debate is of central importance. It is possible that integrated over cosmic time - accretion onto supermassive black holes has produced as much total radiant energy as nuclear burning in stars. Future multi-wavelength observations of the sources detected by ISO, SCUBA, and SIRTF will go a long ways towards settling this crucial issue.

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