THE GREAT DEBATE: STARBURSTS AS THE ENERGY SOURCE OF ULTRALUMINOUS INFRARED GALAXIES

R. D. JOSEPH
Institute for Astronomy, University of Hawaii
2680 Woodlawn Drive Honolulu HI 96822 U.S.A.

1. Introduction

I must say at the outset, I greatly admire my good friend and colleague Dr. Sanders for having the temerity, if not the good sense, to argue for the "monsters" side of this debate. Our conference organizing committee has re-phrased the classical "starbursts vs. monsters" controversy as "monsters vs. babies." Dr. Sanders is therefore effectively taking a position supporting monsters and against motherhood, and I cannot think of an occasion when this has proved to be a wise or effective debating strategy.

One is then led to inquire why someone would take such a position. I believe anyone who teaches elementary astronomy or gives lectures to the public can tell you why: black holes have a mystique, and the less a person understands about fundamental physics the more awestruck they seem to be by the mysteries of black holes. There may be a professional cachet associated with black holes as well. If someone you meet at a party asks you what you do and you say "I am doing research on the effects of black holes," the likely response (from someone aged less than 30 yr) will be, "Wow! Cool!" On the other hand, if you reply, "I am studying baby stars," there is likely to be dead silence while the person ruminates on what intellectual deficiencies keep you from studying more mature and complex stars and whether this may also indicate a predilection for molesting young children. On a more professional level, I will leave to your imaginations the response of a journal editor to a paper with "Baby Stars" in the title, compared to a title with "Supermassive Black Holes" featured prominently.

Be that as it may, we have a debate to get on with, and so I must give you the perspective of the starburst study group whose deliberations took place in the Blue Tower Room. Although we do not believe starbursts are the entire story in attempting to understand ultraluminous infrared galaxies (ULIRGs), we do find the evidence tending to favor starbursts as the principal and dominant energy source in ULIRGs.

2. Evidence that ULIRGS Are Predominantly Powered by Starbursts

First, we must be clear about definitions. We take ULIRGs to be the galaxies detected by IRAS (essentially all at 60 μm) with $L_{\rm IR} \geq 10^{12} L_{\odot}$. Starbursts are an episode of massive star formation that is sufficiently recent that most, if not all, of the upper main sequence of the initial mass function is still present. The ultraviolet radiation of these stars is absorbed by dust and re-radiated in the infrared to provide the large infrared luminosities observed. Monsters are active galactic nuclei (AGNs) in which the luminosity is produced by accretion onto a putative supermassive black hole, and again the high-energy radiation produced is absorbed by dust and re-radiated in the infrared.

2.1. QUALITATIVE EVIDENCE POINTING TO THE UBIQUITOUS PRESENCE OF YOUNG STARS IN ULIRGS

One of the most widely used diagnostics to distinguish starbursts from an AGN is whether spectroscopy of the nucleus shows broad permitted lines that are the *sine qua non* of AGN, or whether the spectra show the low-excitation emission lines characteristic of starbursts. When broad optical lines were generally not found in ULIRGS those committed to the "monsters" hypothesis argued that there must be sufficient extinction that the broad line region is undetectable. This argument has been tested by near-infrared and mid-infrared spectra of substantial samples of LIRGs and ULIRGs. Goldader *et al.* 1995 searched for broad Brγ in a nearly complete sample of 13 ULIRGs and *found no new broad-line objects despite the fact that the extinction is ten times smaller at 2 μm than it is in the visible;* the two broad-line objects they detected had already been found to have broad hydrogen lines in the visible. Lutz *et al.* (1998) carried out mid-infrared (10 μm) spectroscopy with ISO with even less extinction than does spectroscopy at 2 μm. They observed a sample of 60 ULIRGs, and found that 13 of the 60 are likely to be powered by AGNs.

Solomon *et al.* (1997) and others have shown there are massive, centrally concentrated molecular discs of size $\sim$500 pc in ULIRGs. Such high-density molecular discs are of course associated with star formation regions. Moreover, the molecular discs have essentially the same spatial extent as infrared emission regions associated with starbursts, which are also $\sim$500 pc (Telesco, 1989). This is further strong circumstantial evidence supporting the presence of massive starbursts in these galaxies.

Sylvan Veilleux and his collaborators (Veilleux *et al.*, 1997) have carried out comprehensive studies of optical and near-infrared spectra of the 1 Jy IRAS sample. This sample includes many ULIRGs, as well as only slightly less luminous infrared-bright galaxies. These spectra show evidence of starbursts in virtually all the galaxies observed, while <30% show any evidence for AGNs.

Superwinds are found in some ULIRGs (e.g., Heckman, 1990). Superwinds are understood to be driven by supernovae, and therefore the presence of superwinds in ULIRGs provides additional circumstantial support for the presence of massive starbursts.

2.2. QUANTITATIVE EVIDENCE THAT STARBURSTS PROVIDE THE PRINCIPAL UNDERLYING ENERGY SOURCE

We turn now from qualitative or circumstantial evidence for the ubiquitous presence of starbursts in ULIRGs to more quantitative evidence that starbursts actually account for the luminosities of ULIRGs.

There is a growing number of population synthesis studies of LIRGs and ULIRGs in which the properties of a putative starburst are constrained by optical and infrared spectroscopic diagnostics (e.g., Rieke *et al.*, 1998; Kennicutt, 1987; Doyon *et al.*, 1994, Goldader *et al.*, 1997). In broad outline all these models show that the luminosity of a starburst population constrained by the spectroscopic diagnostics fully accounts for the bolometric (i.e., infrared) luminosities of these galaxies. There is no evidence for or need for an additional energy source from an AGN.

There are several tight correlations between infrared luminosity and other measured properties of infrared-bright galaxies which are generally understood to arise because the infrared luminosities are powered by starbursts. The first of these is a correlation between Brγ and infrared luminosity (Goldader *et al.*, 1997). In this case the proportionality between hydrogen recombination lines and total luminosity can be understood in context of starburst model, and it is difficult to see how such a correlation could arise if the infrared luminosity were powered by AGNs. Since this correlation extends to the high infrared luminosities exhibited by ULIRGs this suggests that there is no discontinuity in the physics and astrophysics when one crosses an infrared luminosity of $10^{12} L_{\odot}$.

The radio-infrared correlation is perhaps an even stronger piece of quantitative evidence that gives support to the starburst side of this debate. The correlation between the flux densities in the far-infrared and the radio continuum at 1.5 GHz is one of tightest correlations in astronomy, and it extends from relatively quiescent spirals to ULIRGs (Sanders & Mirabel, 1996). It can be understood in terms of an underlying starburst, with the radio synchrotron radiation arising from supernovae associated with the starburst (e.g., Bicay *et al.*, 1995). Investigations of the radio-infrared correlation in Seyfert galaxies (cf., Roy *et al.*, 1998) show that Seyferts generally exhibit a poor correlation. In detail, those Seyferts lacking compact radio cores tend to follow the same radio-infrared correlation as normal spirals do, whereas those with compact radio cores do not. This is easily interpreted by observing that when the AGN is energetically insignificant the radio-infrared correlation is maintained by an associated starburst, whereas when the AGN is energetically dominant the radio-infrared correlation is poor. In summary, even for those ULIRGs that show evidence for the presence of an AGN, if the ULIRGs fall on the radio-infrared correlation, it is likely that the underlying energy source is dominated by a starburst, rather than the AGN, which may also be present. Thus, the radio-infrared correlation and its extension into the ULIRG regime provides a strong quantitative indication that ULIRGs are dominantly powered by starbursts.

2.3. CONSISTENT FAILURES TO FIND AGN SIGNATURES IN A SIGNIFICANT FRACTION OF LUMINOUS INFRARED GALAXIES OVER PAST DECADE

Even if one finds evidence for the presence of AGNs in ULIRGs, this does not demonstrate that the AGNs are the dominant underlying energy source. Indeed, it is well known that starbursts and AGNs often appear together in galaxies at lower luminosity, and it would not be surprising if both phenomena were found in ULIRGs. However, there has been a signal failure to find broad lines or other diagnostics indicative of the presence of AGNs in any but a minor fraction of various samples of LIRGs and ULIRGs over many years, and this has continued to be an embarrassment to those Dr. Sanders is representing. Rather than accept the obvious, the tendency has been to blame the failure to confirm this hypothesis on the presence of more and more dust.

When AGN features were not found in optical spectroscopy, it was because they were buried in extinction.

When such features were not found in near-infrared spectroscopy with 10 times less extinction (e.g., Goldader *et al.*, 1995, 1997), the claim was that AGNs are buried in even more dust.

Mid-infrared spectroscopy should penetrate many more magnitudes of dust extinction, but of 60 ULIRGs studied by Lutz *et al.* (1998) at 10 μm, as discussed above, these investigators found that AGNs were the most probable energy source in only 13 of the 60 ULIRGS observed. Is there so much dust the putative AGNs are hidden even at 10 μm?

Hard x rays should certainly penetrate any reasonable column of dust, but in a hard x-ray survey of 10 luminous infrared galaxies using ASCA, evidence for AGNs was found in only 5 galaxies. Of these 5, the AGN contribution to the total luminosity was found to be significant only in 3 of the galaxies in the sample (Nakagawa, 1998). Thus based on hard x-ray measurements, only 3 of the 10 galaxies exhibited a significant AGN contribution to the luminosity. In the remainder the x-ray emission is interpreted to be due chiefly to starburst activity.

Radio searches for buried AGNs should also penetrate any reasonable amount of dust, but results so far reveal evidence for starbursts for most ULIRGs (Condon *et al.*, 1991; Smith *et al.*, 1998). Particularly apposite are the recent results by Smith *et al.* (1998), who carried out a VLBI survey for 31 luminous infrared galaxies. They find that for all galaxies except Mkn 231 simple starburst models can account for the far-infrared luminosity. In a detailed analysis of 10 objects, they find 6 can be plausibly explained as starbursts, 3 are hybrid with a starburst and an AGN likely present, and only one object is a *bona fide* AGN.

We would certainly concede there was plausibility to the speculation that monsters might dominate the energy generation in ULIRGs when this hypothesis was proposed a decade ago. But really, after an unbroken series of failed tests of the AGN hypothesis, while the starburst hypothesis continues to be supported by similar diagnostic tests, it now seems only a kind of petulant obstinacy to cling to the shreds of the AGN hypothesis.

2.4. SUMMARY

Virtually every observational technique in every spectral region provides either qualitative or actual quantitative evidence for the ubiquitous presence of starbursts in luminous infrared galaxies.

In stark contrast, virtually every observational technique in every spectral region *fails* to reveal even qualitative evidence for underlying AGN activity for a significant fraction of luminous infrared galaxies. With each failure, the true believers invoke yet more extinction.

Reasonable people that we are, those of us in the "starbursts camp" will concede that monsters may sometimes be present in both LIRGs and in ULIRGs. But the evidence is overwhelming that starbursts provide the *majority* of the energy generation in the *majority* of ULIRGs. AGNs, even when they are present, seem to be relatively insignificant in astrophysical terms.

3. Are ULIRGs Always, Sometimes, or Never the Precursors of QSOs?

The conference organizers have also requested we consider three related questions in the context of this debate, and we consider these questions in this section and the next two sections.

We note at the outset that the opposition must answer the question, "Are ULIRGs always, sometimes, or never the precursors of QSOs?" with an unqualified "always" since their position is that ULIRGs are QSOs buried in extinction.

We take the more moderate position that in science one must go by the evidence. So far there seems to be zero evidence to support the "always" that Dr. Sanders and his followers must advocate. Moreover, there is compelling evidence against it. Examples follow.

3.1. FAILURES OF THE ULIRG-QSO HYPOTHESIS

First, since ULIRGs are agreed to arise from mergers, if they eventually appear as QSOs when the dust disappears, the QSOs should retain morphological evidence of their merger history, such as the very long-lived fossil HI tails; every QSO should have an associated photo-ionized nebula. This prediction fails utterly.

Second, QSOs are AGNs, with no essential differences from Seyferts. They should then share a common generic process with Seyferts. But there is no solid evidence supporting a significant association of interactions with Seyferts, despite years of attempts to find one. Now, one point on which Dr. Sanders and I do agree is that ULIRGs are largely, if not entirely, triggered by mergers. If Dr. Sanders is therefore to argue that ULIRGs *always* are buried QSOs, then in effect he is proposing a different generic process for QSOs than for other types of AGNs, and this change in generic process magically takes place at $L_{\rm IR} \geq 10^{12} L_{\odot}$. While Dr. Sanders may choose to swim against the tide of unification in AGN astrophysics, it seems implausible, and it is certainly at odds with Occam's Razor, a heuristic principle that has often proved to be a valuable guide in science.

4. Do ULIRGs Follow a Merger Sequence from Colliding Disc Galaxies to Produce Ellipticals?

A second question our organizers asked us to consider in this debate is, "Do ULIRGs follow a merger sequence from colliding disc galaxies to produce ellipticals?" This is pertinent to the starbursts vs. monsters controversy because there is growing evidence that mergers of spirals do turn into ellipticals.

We argue that an underlying starburst is an essential ingredient in this process. Starbursts provide large-scale superwinds (cf., Heckman, 1990) that can drive gas and dust out of the merger remnant to produce the characteristic low gas and dust content of ellipticals (Graham *et al.*, 1984).

AGNs by contrast produce highly collimated outflows at best. These punch holes in the interstellar medium, as incorporated in the "unified model," and would not clear much of the residual interstellar gas and dust from the component spirals in the merger. As a result, it is difficult to see how ULIRGs can be part of an evolutionary sequence beginning with the mergers of spirals and culminating in formation of ellipticals, if the dominant energy generation in ULIRGs is produced by AGNs.

In summary, we all agree that the mergers that produce ULIRGs also do evolve into objects resembling ellipticals. But this scenario only makes astrophysical sense provided the ULIRGs are predominantly powered by an underlying starburst.

5. Are ULIRGs Local Examples of the High-Luminosity Tail of Mergers at High Redshift?

I must admit that, initially, this question left those of us confined in the Blue Tower at Ringberg somewhat stumped. We take "mergers at redshifts 1–4" to refer to "Lyman-break galaxies" (e.g., Steidel *et al.*, 1996), since these galaxies display the morphologies associated with interactions and mergers. This question is then relevant to the starbursts vs. monsters controversy if we ask, "What evidence is there for energy generation by starbursts or AGN in Lyman-break galaxies?"

The spectra of Lyman-break galaxies are strikingly similar to those of nearby star-forming galaxies. Starburst population synthesis models constrained by the far-UV continua give star formation rates in the range expected, and it is generally agreed that these objects are undergoing starbursts. There is no noteworthy evidence of AGN features in these galaxies (Steidel *et al.*, 1996).

In summary, the evidence is that Lyman-break galaxies are undergoing star-formation events very much like local starburst galaxies. If ULIRGs are local examples of the high-luminosity tail of these objects at higher redshift, then ULIRGs, too, are largely powered by starbursts.

6. The "Complete Sample of Nearby ULIRGs"

The monsters study group produced a "complete sample" of five nearby ULIRGs, four of which they argue have an energy source powered by an AGN based on several diagnostics. This seemed to be the strongest argument in Dr. Sanders' courageous attempt to find support for the AGN hypothesis. How well does this support the hypothesis? The problem of course is the small-number statistics. It turns out that a ratio of four AGNs and one starburst in a sample of five does not provide a very strong test of the hypothesis that AGNs dominate the larger population. In fact, at the 95% confidence level one cannot rule out there being 65% starbursts and 35%

AGNs, given this result for a sample of five objects. (I thank my colleague John Sender for doing the statistical calculation.)

This very weak confidence limit is consistent with one's suspicion that the results might be quite sensitive to the choice of a volume over which a sample is chosen. For example, Dr. Sanders himself produced the original complete flux-density limited sample of ten ULIRGs (Sanders *et al.*, 1988). At best only 20% or so show any evidence for the presence of an AGN, based on near-infrared spectroscopy (Goldader *et al.*, 1995). Lutz *et al.* (1998) obtained 10 μm spectroscopy with ISO for a sample of 60 ULIRGs, and found ∼20% of the sample are probably powered by AGN. "Complete" samples of five can be quite misleading!

7. Conclusions

The evidence is overwhelming, based on every conceivable diagnostic tool—optical spectroscopy, near-infrared spectroscopy, mid-infrared spectroscopy, VLA and VLBI radio images, x-ray observations—as well as in consideration of astrophysical consistency and plausibility from a number of points of view, that, in the majority of cases, ULIRGs are largely powered by starbursts. Even when there is evidence for the presence of an AGN, it is seldom obvious that the AGN provides the majority of the energy generation in these galaxies. The starbursts group thus submits this evidence to support its contention that starbursts are chiefly responsible for the prodigious energy generation in ultraluminous infrared galaxies.

8. Acknowledgements

I should like to thank the participants of this workshop who attended the starbursts study group in the Blue Tower Room at Ringberg for their ideas and discussion. I hope I have been able to assimilate and present their contributions persuasively. I should also like to thank Reinhard Genzel and the Scientific Organizing Committee for coming up with the novel idea of this debate. It helped to make an extraordinarily lively workshop even more engaging. I don't know that anyone's prejudices have been changed, but it is clear, at least to me, that the issues are a bit more complex and subtle than I perhaps realized before arriving at Ringberg.

I should like to thank my colleague and collaborator, Dave Sanders, for providing stimulating discussion and dialogue on these issues over the years; his comprehensive knowledge of this subject is truly impressive. Finally, it is a pleasure to thank Ms. Louise Good for her expert help in preparing and editing this manuscript.

References

Bicay, M. D., Kojoian, G., Seal, J., Dickinson, D. F., & Malkan, M. A. 1995, ApJS, 98, 369

Condon, J. J., Broderick, J. J. 1991, AJ, 102, 1663

Doyon, R., Joseph, R. D., & Wright, G. S. 1994, ApJ, 421, 101

Goldader, J. D., Joseph, R. D., Doyon, R., & Sanders, D. B. 1995, ApJ, 444, 97

Goldader, J. D., Joseph, R. D., Doyon, R., & Sanders, D. B. 1997, ApJ, 474, 104

Graham, J. R., Wright, G. S., Meikle, W. P. S., Joseph, R. D., & Bode, M. F., 1984, Nature, 310, 213

Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833

Kennicutt, R. C., Jr., Roettiger, K. A., Keel, W. C., Van Der Hulst, J. M., Hummel, E. 1987, AJ, 93, 1011

Lutz, D., Spoon, H .W. W., Rigopoulou, D., Moorwood, A. F. M., & Genzel, R. 1998, ApJ, 505, L103

Nakagawa, T., Kii, T., Fujimoto, R., Miyazaki, T., Inoue, H., Ogasaka, Y., Arnaud, K., & Kawabe, R. 1999, in Galaxy Interactions at Low and High Redshift, ed. J. E. Barnes & D. B. Sanders (Dordrecht: Kluwer), 341

Rieke, G H., Lebofsky, M. J., Thompson, R. I., Low, F. J., Tokunaga, A. T. 1980, ApJ, 238, 24

Roy, A. L., Norris, R. P., Kesteven, M. J., Troup, E. R., & Reynolds, J. E. 1998, MNRAS, 301, 1019

Sanders, D. B., & Mirabel, I.F. 1996, AARA, 34, 749

Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74

Smith, H. E., Lonsdale, Colin J., Lonsdale, Carol J. 1998, ApJ, 492, 137

Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, Ap.J., 478, 144

Steidel, C .C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17

Telesco, C. M., Dressel, L. L., Wolstencroft, R. D. 1993, ApJ, 414, 120

Veilleux, S., Sanders, D. B.; Kim, D.-C. 1997, ApJ, 484, 92