An AGN Hertzsprung-Russell Diagram

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Abstract. Detailed examination of the balance between star-formation and nuclear activity in AGN and starburst galaxies leads to the composition of an Hertzsprung-Russell diagram in which possible evolutionary tracks can be drawn. It is likely that these tracks also relate to the level of obscuration.

1. Introduction

The question I’d like to address is whether there is a physical reason behind the resemblance of the cosmic star-formation history diagram, the ‘Madau-plot’, and the evolving QSO space density diagram (e.g., Shaver et al. 1996). Given that the shapes of these plots – in particular the $z \sim 2.5$ peaks – are similar, could it be that star-formation and nuclear activity in galaxies are more intimately related than we have believed so far? Rosa Gonzalez Delgado and George Rieke (these Proceedings) have already presented evidence that such is the case for Seyfert galaxies – I will add QSOs and discuss the AGN-starburst symbiosis within the framework of an Hertzsprung-Russell diagram analogon. A more complete account of the issue and a more thorough presentation of the rationale can be found in Barthel (2001).

2. Star-formation and FIR SEDs

Star-formation is mainly studied in the restframe ultraviolet-blue part of the spectrum, where clear signatures from young star populations can be found. However, such signatures will remain hidden when the star-formation occurs in a dusty region. In that case only thermal reradiation of the the hard ultraviolet photons by the dust can reveal the obscured star-formation. Data taken with IRAS and more recently ISO have beautifully demonstrated the importance of this mechanism: it has for instance revealed the class of ULIRGs (e.g., Sanders & Mirabel 1996) and the starburst activity located in between the Antennae galaxies NGC 4038 and NGC 4039 (Vigroux et al. 1996).

While normal galaxies display cold dust (heated up to $\sim$20K by the interstellar radiation field primarily due to the old population), starburst galaxies display warmer dust ($\sim$50K) related to the visible or unvisible young star population. The luminosity of the latter dust correlates with the (mostly) diffuse radio synchrotron emission, through the radio-FIR correlation (e.g., Condon 1992). This radio-FIR correlation is well known, but in my view not yet appre-
ciated to its fullest extent – recall that only radio waves and hard X-rays can penetrate the inferred walls of extinction! From their far-infrared SEDs, normal and starburst galaxies are characterized with steeply rising $25\,\mu m$ to $60\,\mu m$ slopes between 1.5 and 3.

Seyfert galaxies have a third dust component: hot dust peaking at $\sim 25\,\mu m$ (De Grijp et al. 1985, Rodríguez Espinosa et al. 1996). This radiation is most likely emitted by the circumnuclear torus dust, being directly exposed to the hard AGN continuum (Rowan-Robinson 1995). I note in passing that this hot dust component is present at comparable magnitude in Seyfert galaxies of Type 1 and Type 2 (Pérez García et al. 1998), thereby proving the presence of hot, circumnuclear dust in Type 1 AGN. This third dust component produces a flattening of the $\alpha_{60\mu m}$ slope, to values in the range 1.0 to 1.5.

Not all AGN, however, have $\alpha_{60\mu m}$ indices in that range. On one hand there is the Blazar class which radiates nonthermal FIR, and can have indices as flat as 0.5. On the other hand there are AGN with an unusually luminous star-formation activity. The extra-strength $60\,\mu m$ component related to this activity steepens the $\alpha_{25\mu m}$ index to values in excess of 1.5 – the compact radio-loud quasar 3C 48 is a prime example (Canalizo & Stockton 2000a).

How general is this enhanced star-formation activity among the QSO population (radio-loud and radio-quiet)?

3. Star-forming QSOs and Seyfert galaxies

Like 3C 48 mentioned above a few more quasars are known to have strong ongoing star-formation. In an infrared color-color diagram (for instance displaying $\alpha_{60\mu m}$ versus $\alpha_{100\mu m}$) these objects are found close to the area occupied by ULIRGs (e.g., Canalizo 2000, Barthel 2001), and so the question emerges as to whether temporal evolution between the classes can occur.

In our study of the AGN-starburst symbiosis my colleagues and I have obtained and analysed deep radio (VLA), optical/nearIR (ESO; La Palma, including Carlsberg Meridian Circle astrometry), as well as improved IRAS data for a sample of 16 Seyfert galaxies having $z < 0.02$, and 27 radio-quiet PG (Palomar-Green) QSOs having $0.02 < z < 0.4$. These complementary samples of active galaxies span a wide, continuous luminosity range of 3.5 orders of magnitude. These luminosities are expressed as $L(12\,\mu m)$, and hence predominantly reflect the AGN strength (e.g., Spinoglio & Malkan 1989). The radio-imaging, reaching noise levels of $\sim 30\,\mu Jy$, as well as the optical astrometry yield AGN positions to a 3$\sigma$ accuracy of $\sim 0.4$ arcsec. This allows comparison of the AGN versus the star-formation driven radio emission. The radio data of these – I stress – radio-quiet active galaxies are being combined with far-infrared photometry, yielding $u$-parameters $\log S_{60\mu m}/S_{6cm}$ (see e.g., Condon & Broderick 1988), which permit assessment of the relative roles of nuclear activity and star-formation. Normal star-forming spirals, obeying the radio-FIR correlation, have $u$ values in the range 2.4–3.0. Most Seyfert galaxies have infrared detections (at 25 and 60$\,\mu m$), in contrast to about half of the PG QSOs. Also the ratios of the 60$\,\mu m$ and blue flux densities were compiled.
Plotting the infrared color as function of the (AGN) luminosity, we see from Fig. 1 that the more luminous QSOs (open symbols) are warmer than the Seyfert galaxies (filled symbols), and we infer that the AGN luminosity must to some extent be driving the objects’ dust temperatures.

Analysis of the $u$-parameters in combination with the radio images subsequently indicates that excess nuclear radio emission, and/or fading diffuse radio emission also leads to warmer dust. This is the case for both the Seyfert and the QSO class, and implies that an extra-strength active nucleus in a galaxy with fading starburst activity also raises the dust temperature. Fig. 2 shows the same distribution as Fig. 1, but with filled symbols now representing the weak-starburst/extra-strength AGN ($u < 2.3$) and the open symbols representing the objects obeying the radio-FIR correlation ($u \geq 2.3$). We note a decrease in the $u$-parameter, in the upward direction in Fig. 2: for all (AGN) luminosities the dust becomes warmer with fading star-formation. The 60 $\mu$m over B-band flux density ratios are in good agreement: a strong decrease is seen, in the upward direction of Fig. 2, implying fading of the cool star-formation related dust component for a given (AGN) B-band luminosity.

4. An Hertzsprung-Russell diagram equivalent?

The objects in Figures 1 and 2 make up a – be it wide – diagonal strip running from bottom left to top right. This strip in turn can be separated in a lower part where star-formation is relatively important, and an upper part where star-formation is relatively unimportant. Classical ULIRGS such as Arp 220 and Mkn 231 are characterized with rather cool dust (see the beginning of Sec-
3) and fall under this lower strip. When rotated by 90°, the figures display luminosity versus temperature, and can thus be considered as the active galaxy equivalent of the classical Hertzsprung-Russell diagram. If the question as for an evolutionary connection between the strongly and the weakly star-forming AGN is a valid one, then also the connection between the AGN and the ULIRGs should be taken seriously (cf. Sanders et al. 1988). Age dating (e.g., Canalizo & Stockton 2000b, Canalizo 2000) may permit to draw the evolutionary tracks. JCMT observations of the molecular gas in QSO hosts are currently being analyzed by our group to test the evolutionary scenario. I conclude that a substantial fraction of AGN displays strong star-formation activity, and note that such is probably not restricted to radio-quiet AGN (e.g., Aretxaga et al. 2001).

5. Implications

If an appreciable, more or less constant fraction of strongly star-forming galaxies develops and reveals an AGN after and/or during the process of intense circumnuclear star-formation, the similarity of the QSO space density and the star-formation history diagram may not be coincidental. Given that the latest versions of the latter (e.g., Calzetti 2001) suggest a non-declining star-formation rate for redshifts \( z = 2 \) to 5, and given the submm indications for even more distant starburst activity (e.g., Dunlop 2001), the hunt for extreme redshift QSOs remains at order.
6. Conclusions

The 60 µm luminosity, when normalized with the 25 µm (or the 12 µm), the blue optical or the radio luminosity, permits assessment of the absolute and relative strength of star-formation and nuclear activity in active galaxies and quasars. The FIR temperature can be combined with measures of the bolometric luminosity to yield an intriguing AGN Hertzsprung-Russell diagram, which among other things suggests that star-formation plays an important role in many AGN. Such photometric ratios can be obtained in a straightforwardly manner for the faint distant objects to be measured in large quantities with upcoming space-infrared missions, such as SIRTF, ASTRO-F and Herschel.

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