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SCUBA observations of Hawaii 167

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ABSTRACT

We present the first submillimetre observations of the $z = 2.36$ broad absorption line system Hawaii 167. Our observations confirm the hypothesis that Hawaii 167 contains a massive quantity of dust, the optical depth of which is sufficient to extinguish completely our ultraviolet view of a central, buried quasar. The submillimetre luminosity and associated dust mass of Hawaii 167 are similar to those of the ultraluminous class of infrared galaxies, supporting the existence of an evolutionary link between these and the active galaxy population. Hawaii 167 appears to be a young quasar that is emerging from its dusty cocoon.

Key words: dust, extinction – quasars: individual: Hawaii 167 – infrared: galaxies.

1 INTRODUCTION

Hawaii 167 was identified in the Hawaii *K*-band survey (Songalia et al. 1994). Displaying a rest-frame ultraviolet spectrum of a young stellar population at $z = 2.34$, Hawaii 167 also possesses broad absorption troughs of both high- and low-ionization species, consistent with the presence of bulk outflows (Cowie et al. 1994). While such features are characteristic of the broad absorption line (BAL) class of quasars, the broad emission lines indicative of an active galactic nucleus (AGN) core are not seen in the ultraviolet spectrum. Infrared spectroscopy, however, does reveal both broad Hα and Hβ (Cowie et al. 1994; Egami et al. 1996), with a redshift of $z = 2.36$. These observations indicate a substantial Balmer decrement (Hall et al. 1997), suggesting that Hawaii 167 is an example of a dust-enshrouded quasar; thought to represent an early evolutionary stage, such systems would appear as fully fledged quasars once all the dust has been removed. During the transition from one phase to another, as dust is blown from a central obscuring torus, the system will appear as a BAL-type quasar. It appears, therefore, that Hawaii 167 provides us with a view of an embryonic quasar. The limited data available on Hawaii 167, however, mean that an accurate determination of its dust mass, total luminosity and true evolutionary status is not currently possible.

In this paper we present submillimetre observations of Hawaii 167, probing the emission from a dusty component. These were obtained as part of a survey of the dust properties of BAL quasars (Lewis & Chapman, in preparation). In Section 2 the details of the observations are presented, while Section 3 discusses the dust content and evolutionary status of Hawaii 167. The conclusions to this study are presented in Section 4.

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2 OBSERVATIONS

We observed Hawaii 167 with the Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. We used the PHOTOMETRY three-bolometer chopping mode described by Chapman et al. (2000) and Scott et al. (2000) to keep the source in a bolometer throughout the observation. This mode has the additional advantage of allowing a check on the apparent detection of a source over three independent bolometers. The observations were taken in 2000 May, using the 450- and 850-μm arrays simultaneously. The alignment of the 450- and 850-μm arrays is not perfect, and we did not include the 450-μm off-beams in our final flux estimate, except to check that the source had off-beam flux consistent with the detection in the primary bolometer.

For our double-difference observations there are instantaneously $N = 3$ beams, with the central beam having an efficiency of unity and the two off-beams having

$$\epsilon = -0.5 \exp\left(-\frac{d^2}{2\sigma_\mathrm{b}^2}\right), \quad (1)$$

where d is the angular distance of the off-beam centre from the source, and σ_b is the Gaussian half-width of the beam. For the secondary bolometer the beam efficiency is simply 0.5. However, distortion in the field results in our chosen third bolometer being slightly offset from the source position, resulting in a beam efficiency of 0.44. Our detection level increases from $\simeq 3.0\sigma$ to 3.7σ, after folding in the negative flux density from the two off-beam pixels.

The effective integration time on source was 1900 ks. The secondary was chopped at 7.8125 Hz with a chop throw at 53 arcsec to keep the source on-bolometer at all times. Pointing was checked before and after the observation on blazars, and a sky-dip was performed to measure the atmospheric opacity directly. The rms pointing errors were below 2 arcsec, while the

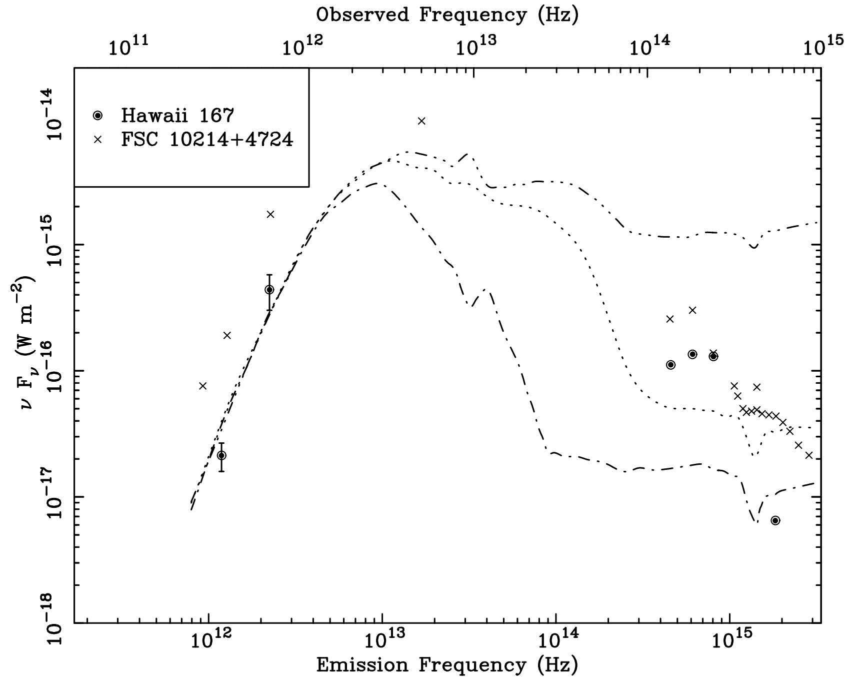

Figure 1. The spectral energy distribution of Hawaii 167 ($z = 2.36$) as compared with the gravitationally lensed ultraluminous galaxy FSC 10214+4724 ($z = 2.28$); no correction for gravitational lensing magnification has been made to these data. The data presented in this paper are denoted with error bars. The curves on each plot represent the dust-enshrouded quasar models of Granato et al. (1996). From top to bottom, these represent viewing angles of polar, 45° and equatorial respectively. The emission frequency corresponds to $z = 2.36$.

average atmospheric zenith opacities at 450 and 850 μm were 1.5 and 0.22 respectively. The data were reduced using the Starlink package SURF (Scuba User Reduction Facility: Jenness & Lightfoot 1998) and our own reduction routines to implement the three-bolometer chopping mode. Spikes were first carefully rejected from the data, followed by correction for atmospheric opacity and sky subtraction using the median of all the array pixels, except for obviously bad pixels and the source pixels. The data were then calibrated against standard planetary and compact H II region sources, observed during the same night. The resulting fluxes were 6.04 ± 1.65 mJy at 850 μm and 66.0 ± 20.7 mJy at 450 μm.

3 DISCUSSION

3.1 Luminosity and dust content

Fig. 1 presents the extant data of Hawaii 167, including the SCUBA data discussed in Section 2. Also included for comparison is the spectral energy distribution (SED) of the $z = 2.28$ ultraluminous infrared galaxy FSC 10214+4724 (Rowan-Robinson et al. 1993); this system is also thought to harbour a dust-enshrouded quasar (e.g. Barvainis et al. 1995). Gravitational lensing has significantly boosted the apparent luminosity of FSC 10214+4724 (e.g. by a factor of 30 in the infrared: Broadhurst & Lehar 1995), although no correction for magnification has been made to its data points in the figure.

Emission from a dusty component can be modelled as a greybody of the form

$$F_\nu \propto \frac{\nu^3}{e^{h\nu/kT} - 1}\left[1 - e^{-(\nu/\nu_0)^\beta}\right], \qquad (2)$$

where ν_0 is the frequency at which the source becomes optically thick (Benford et al. 1999); the shape of the greybody is only mildly sensitive to the value of ν_0 and we adopt the value of 2.4 THz (Hughes et al. 1993). The Hawaii 167 data are consistent with a greybody temperature of $T = 88 \pm 25$ K and $\beta = 2.8 \pm 1.1$; while these values differ from 'typical' greybody fits to AGN, which result in values of $T = 50$ K and $\beta = 1.5$ (Benford et al. 1999), the differences are not significant given the errors.

Following the recipe of McMahon et al. (1999), the 850-μm flux was used to calculate the following physical properties:[1] a far-infrared luminosity of $L_{\rm FIR} \sim 1.1 \times 10^{13}\, h_{50}^{-2}\, {\rm L}_\odot$ and an associated dust mass of $M_{\rm d} = 3.3 \times 10^8\, h_{50}^{-2}\, {\rm M}_\odot$ (assuming a dust temperature of 50 K). Such values place Hawaii 167 firmly in the ultraluminous class of infrared galaxies (Sanders & Mirabel 1996). If the observed infrared emission were solely due to stars, it would correspond to a star formation rate of $\sim 1000\, {\rm M}_\odot\, {\rm yr}^{-1}$ (this is an upper limit, as Hawaii 167 obviously contains a central AGN source which also acts to heat the dust). Hawaii 167 displays no evidence of gravitational lensing, appearing point-like at a point spread function (PSF) scale of 0.5 arcsec (Cowie et al. 1994), and hence its inferred properties have not been magnified and we can conclude that Hawaii 167 is truly an ultraluminous system.

While we have added to the SED of Hawaii 167, the data are still sparse and a detailed determination of the underlying physical properties and geometry is unwarranted. Instead, we compare its SED with published models of dust-enshrouded quasars. The lines in Fig. 1 represent such models for ultraluminous infrared galaxies (Granato, Danese & Franceschini 1996). Consisting of a optically thick torus of dust, extending over several hundred parsecs from the AGN core, each curve represents a differing viewing angle: the dot–dashed line is an equatorial view which maximally extinguishes the optical–ultraviolet light from the quasar, while the

[1] $\Omega_0 = 1$, $\Lambda_0 = 0$, $H_0 = 50\, h_{50}$ km s^{-1} Mpc^{-1} assumed throughout.

triple-dot–dashed line is a polar view with an unobstructed view of the AGN core. The dotted line represents an intermediate case, with a viewing angle of ~45°. A substantial portion of the radiation from the central quasar is reprocessed into the submillimetre/infrared by dust in the torus. Such models reasonably reproduce the SED characteristics of FSC 10214+4724 (equatorial view), as well as other ultraluminous systems such as the cloverleaf quasar, H1413+117 (polar view), and IRAS 09104+4109 and IRAS FSC 15307+3252 (intermediate view). In Fig. 1, these curves have been normalized to the data presented in this paper. It is important to note that Egami et al. (1996) conclude that the (rest-frame) ultraviolet emission in Hawaii 167 arises solely in a stellar population, with no contribution from the AGN core because of complete obscuration by the circumnuclear dust. As all the models of Granato et al. (1996) predict that *some* radiation from the central regions must be visible in the ultraviolet, none can accurately describe the SED of Hawaii 167, but this may be due to the parameter set employed in the modelling; the inclusion of more dust, or changing the opening angle of the torus, may bring better agreement between the models and the data. It is apparent, however, that combining the submillimetre and infrared data favours a model with an intermediate viewing angle on to the obscuring torus. Again, scaling from the models, the resulting dust mass in Hawaii 167 is $\sim 3 \times 10^7\,\mathrm{M}_\odot$. Without more data over the SED of Hawaii 167, this value possesses a significant uncertainty, but does indicate that Hawaii 167 harbours a vast quantity of dusty material.

3.2 Broad absorption lines

The nature of the broad absorption lines seen in the rest-frame ultraviolet of Hawaii 167 presents an interesting problem. In the 'standard model' of BAL quasars the prominent absorption lines are the result of the central continuum emission being observed through material that is ablated from an obscuring torus by the action of the central quasar (e.g. Barvainis et al. 1995). In Hawaii 167 the ultraviolet view of the central quasar is completely obscured and the AGN radiation cannot be responsible for accelerating the BAL material. A potential solution, however, is that the BAL material is driven from the outer dusty regions by hot young stars. The requirement of two sources for the driving force of the BAL material during different stages of evolution of the system does, however, seem a little contrived, but we can currently offer no solution to the problem.

3.3 Evolutionary state and further study

In terms of infrared luminosity, and hence associated dust mass, Hawaii 167 is similar to other ultraluminous systems (Rowan-Robinson 2000), and it is only the detection of broad emission lines in the infrared that directly reveals the presence of a quasar at its core. Such a picture is consistent with there being an evolutionary link between the two populations (e.g. Sanders & Mirabel 1996). Here, an initial burst of star formation is triggered by the merger between two gas-rich systems. The merger channels gas into the central regions of the remnant, forming and feeding a quasar core. This AGN, however, is obscured by dust, the detritus of the starburst; it is at this stage that we find Hawaii 167. The dust is ablated from the torus owing to radiation from the quasar core, eventually clearing and revealing a 'normal' quasar.

Further clues to the nature and geometry of Hawaii 167 will be gleaned from polarization studies. As demonstrated with FSC 10214+4724 (Goodrich et al. 1996), such observations can reveal the presence of broad emission features, and hence an AGN core, the light of which has been scattered from a exterior region (Barvainis et al. 1995). The identification of a scattered view of the central engine will imply that the AGN core is not completely obscured.

4 CONCLUSIONS

We have presented new submillimetre photometry of the high-redshift, broad absorption line system Hawaii 167. These observations confirm that this system consists of a quasar which is enshrouded in a massive ($\sim 10^7$–$10^8\,\mathrm{M}_\odot$) quantity of dust. With an inferred infrared luminosity of $\sim 10^{13}\,h_{50}^{-2}\,\mathrm{L}_\odot$, Hawaii 167 is a member of the ultraluminous class of infrared galaxies. The more extreme members of this family, namely FSC 10214+4724 and H1413+117, have been found to be gravitational lenses. Hence their apparent luminosities have been significantly magnified. Considering this, Hawaii 167 represents an intrinsically more luminous source than these objects.

The identification of Hawaii 167 as an ultraluminous infrared galaxy provides more supporting evidence for there being an evolutionary link between these and the AGN family. While presenting us with the rare view of a embryonic quasar in the process of shedding its dusty cocoon, data on Hawaii 167 are currently quite sparse and more observations are required before detailed modelling can be undertaken.

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