*The Interplay among Black Holes, Stars and ISM*
*in Galactic Nuclei*
*Proceedings IAU Symposium No. 222, 2004*
*T. Storchi-Bergmann, L. C. Ho & H. R. Schmitt, eds.*

DOI: 10.1017/S1743921304002984

# The infrared universe: The cosmic evolution of superstarbursts and massive black holes

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**Abstract.** Our view of galaxy evolution has been dramatically enhanced by recent deep field surveys at far-infrared and submillimeter wavelengths. Current evidence suggests that the number density of the most luminous far-infrared sources evolves strongly with redshift, and that the luminosity density in the far-infrared/submillimeter may exceed that in the optical/ultraviolet by factors of $3 - 10$ at redshifts $z > 1$. If true, then as much as 80-90% of the "activity" in galaxies at $z > 1$ may be hidden by dust. Surveys of complete samples of luminous infrared galaxies in the local Universe show that the majority, if not all objects with $\log(L_{\rm ir}/L_{\odot}) \gtrsim 11.6$, appear to be major mergers of molecular gas-rich disks accompanied by dust-enshrouded nuclear starbursts and powerful AGN. If the majority of the deep-field sources are simply more distant analogs of local luminous infrared galaxies, then we may be witnessing at $z \sim 1 - 3$ the primary epoch in the formation of spheroids and massive black holes. This major event in galaxy evolution is largely missed by current deep optical/ultraviolet surveys.

## 1. Introduction

This review summarizes the properties of luminous infrared galaxies (LIGs) – objects with $\log(L_{\rm ir}/L_{\odot}) \gtrsim 11$ ($H_{\rm o} = 75\,{\rm km\,s^{-1}\ kpc^{-1}}$) – in the local Universe, as determined from extensive ground-based follow-up studies of complete samples of far-infrared selected galaxies from the Infrared Astronomical Satellite (IRAS) All-Sky 60$\mu$m survey. It also presents more recent results from follow-up studies of the faint far-infrared source population detected in deep-fields observed with the Infrared Space Observatory (ISO) at 170$\mu$m, and makes brief mention of the latest results from on-going studies of the faint submillimeter source population detected at 850$\mu$m with the Submillimeter Common User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT). Evidence is then presented that ULIGs in the local universe are plausibly an important stage in the evolution of nuclear superstarbursts and the building of massive black holes.

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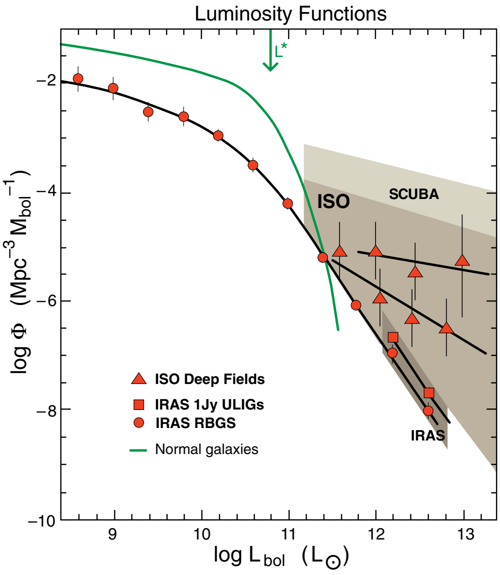

**Figure 1.** The luminosity functions (LFs) for infrared selected galaxies. The thick solid curve and filled circles represents the Local LF as determined from all 635 galaxies in the *IRAS* RBGS (Sanders et al. 2003). The filled squares represent the LF of relatively nearby ULIGs as determined from the *IRAS* 1-Jy sample of 118 ULIGs (Kim & Sanders 1998). The thin curve represents the Schechter function for optically selected normal galaxies in the local Universe (Schechter 1976). The dominance of infrared galaxies with $\log(L_{\rm ir}/L_\odot) \gtrsim 11.6$ over the rapidly declining high-luminosity tail of the Schechter function illustrates the dominance at the highest luminosities of luminous and ultraluminous infared galaxies over optically selected galaxies, even in the local Universe. But *more importantly*, as illustrated by the recently determined LFs of IR-selected galaxies at higher redshifts (ISO and SCUBA data), *it is this high-luminosity tail of the IR-galaxy LF that strongly evolves with redshift increasing by nearly 3 orders of magnitude (!) between $z = 0$ and $z \sim 2.5$ (Sanders 2004), while the LF for lower luminosity galaxies shows little or no redshift evolution.* Studying the low-z IRAS galaxies at $\log(L_{\rm ir}/L_\odot) \gtrsim 11.6$, therefore offers us the chance of understanding the properties of their much more numerous higher$-z$ analogs, which at $z \gtrsim 1$ appear to *dominate* the total luminosity output of all galaxies.

## 2. The luminosity function of infrared selected galaxies

Figure 1 presents the luminosity function (LFs) for infrared selected galaxies for comparison with the Schechter Function for optically selected galaxies. The figure caption gives a detailed description of and references for the infrared data samples used. Figure 1 clearly shows that at $\log(L_{\rm ir}/L_\odot) \gtrsim 11$, LIGs , although rare in the local Universe, become much more numerous than optically selected galaxies. In addition, at higher redshift, this high-luminosity tail becomes much more prominent, to the point where LIGs appear to dominate the total FIR/Submm luminosity output of all infrared selected galaxies at $z \gtrsim 1$. The nature of the object which make up this strongly evolving high luminosity tail of the far-infrared LF has now been revealed through extensive multi-wavelength follow-up studies of complete samples of sources.

## 3. Multiwavelength studies of complete local samples of LIGs/ULIGs

Morphology Perhaps the most impressive result from studies of LIGs is that recently completed by Ishida (2004) who obtained deep optical ($BVI$) images of a complete sample of LIGs from the IRAS Revised Bright Galaxy Sample (RBGS). As the nearest and

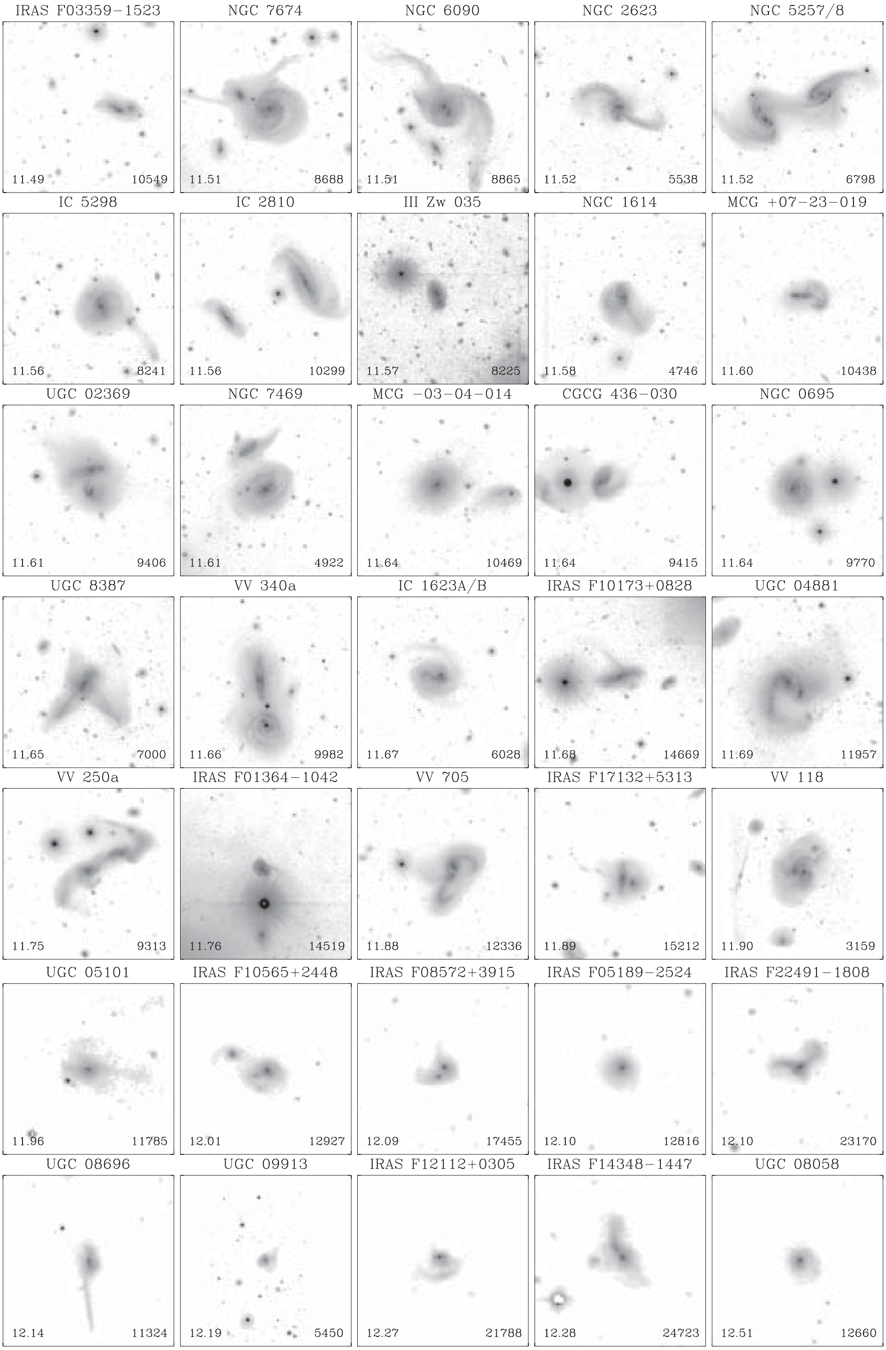

**Figure 2.** "Open filter" optical ($B$+$V$+$I$) images from Ishida (2004) of a complete subsample of objects (35) in the *IRAS* RBGS with $\log(L_{\rm ir}/L_\odot) = 11.49 - 12.51$ sorted in order of increasing $L_{\rm ir}$ (left-to-right, top-to-bottom). Each panel represents a fixed FOV (100 kpc × 100 kpc) at the distance of the object. The primary object name (top), measured redshift (lower right) and computed $\log(L_{\rm ir}/L_\odot)$ (lower left) have been taken from the *IRAS* RBGS (Sanders et al. 2003).

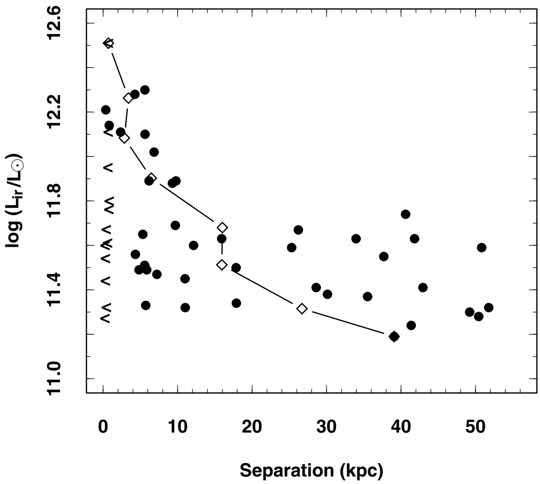

**Figure 3.** Projected nuclear separations (kpc), as measured from K-band images (Mazzarella et al., in preparation) for the complete subsample of 66 galaxies with $\log L_{\rm ir}/L_{\odot} = 11.11 - 12.51$ in the IRAS RBGS studied by Ishida (2004). The solid line represents the median projected nuclear separation for the IRAS RBGS galaxies in $\Delta(L_{\rm ir}) = 0.25$ dex bins.

brightest examples of LIGs, the RBGS galaxies have been the most amenable to studies at other wavelenghts. Figure 2 presents a compete subset of "open-filter" $(B + V + I)$ images of 35 RBGS galaxies ordered by increasing infrared luminosity, illustrating the fact that all of the objects with $\log{(L_{\rm ir}/L_{\odot})} > 11.5$ appear to be strongly interacting merger systems of relatively equal mass ($\sim L^*$) spirals.

Figure 3 illustrates that the more luminous the merger system the more advanced the merger. The distribution of inter-nuclear distances, $P(d)$, for the merger pairs, once corrections for sample volume have been made, is consistent with the expected distribution of orbit decays given that merger simulations show that $P(d) \propto \tau_{\rm decay} \propto d$ (Barnes 2001). This would also suggest that in these merger systems we are indeed witnessing a progressive increase in $L_{\rm ir}$ with time ($\tau$). Assuming a typical $\Delta V$ of $\sim 50\,{\rm km\,s^{-1}}$ (e.g. Sanders & Mirabel 1996) and the distribution of separations shown in Figure 3, the median merger timescale for the objects at $\log{(L_{\rm ir}/L_{\odot})} = 11.5$ would be $\sim 3 \times 10^8$ yrs.

Molecular gas content Equally interesting, when considered in the context of the apparent merger sequence for LIGs, is both the large molecular gas masses found in all of the LIGs, plus the increasingly larger nuclear concentrations of molecuclar gas with increasing infrared luminosity. Millimeterwave observations in the lower rotational transitions of CO of the majority of the objects in Figure 2 show that *all* of these systems are molecular gas rich (e.g. Sanders, Scoville & Soifer 1991), with mean gas masses of $\log M(H_2)/M_{\odot} \sim 10.1$, or approximately 3 times the total molecular gas mass of the Milky Way. A substantial fraction of these sources have now been observed at much higher resoltuion with millimeterwave interferometers, with the resulting maps showing an increasing concentration of nuclear molecular gas in the most luminous systems. Figure 4 illustrates one of the most extreme cases where nearly all of the molecular gas has been funneled into the inner 1–2 kpc of the merged system.

Spectroscopy Optical and near-infrared spectroscopy of LIGs in the RBGS shows that while the great majority of LIGs have spectra consistent with ongoing diskwide as well as nuclear starbursts, the percentage of objects whose spectra show strong evidence for a dominant AGN increases with increasing $L_{\rm ir}$. Figure 5 shows that ~50% of objects with $\log\, L_{\rm ir} > 12.3$ are classified as either Seyfert 1 or 2.

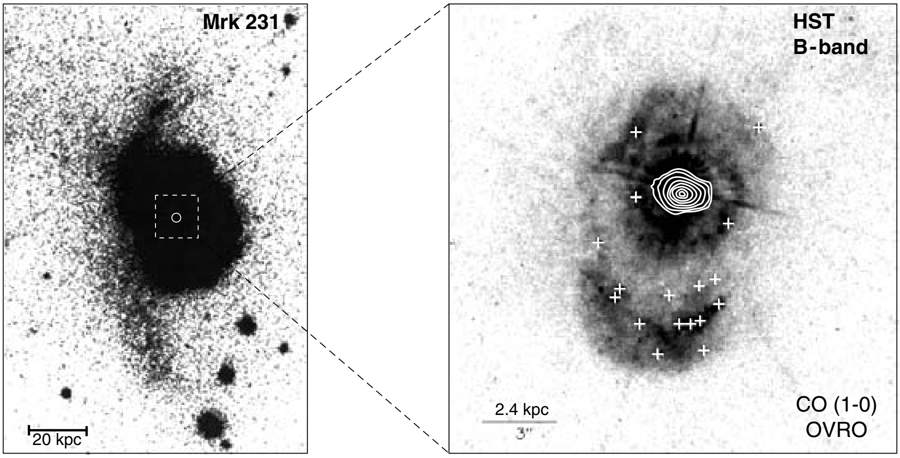

**Figure 4.** The “IR-QSO” Mrk 231. (left panel) - optical R-band image (Sanders et al. 1987) and size of central molecular gas concentration (circle). (right panel) - HST B-band image and identified stellar clusters (‘+’) from Surace et al. (1998).The high resolution CO contours are from Bryant & Scoville (1996).

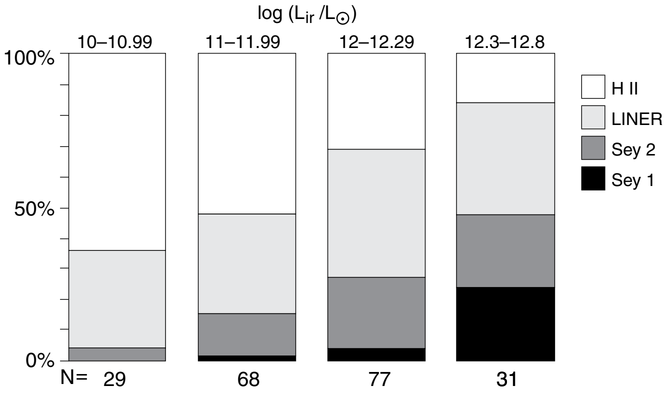

**Figure 5.** The optical spectral classification of infrared galaxies (from the IRAS RBGS and 1-Jy samples) versus infrared luminosity (Veilleux, Kim & Sanders 1999). These classifications were based on ground-based spectra covering the wavelength range ~3500Å–8800Å, using a 2″ slit centered on the K-band “nucleus”.

Equally intriguing is the fact that near-infrared spectroscopy shows that an even larger fraction of ULIGs harbor a strong Seyfert nucleus. Veilleux, Sanders & Kim (1999) found that nearly all of the object with “warm” far-infrared colors ($S_{60\mu m}/S_{100\mu m} > 0.25$) which did not show evidence for a Seyfert nucleus at optical wavelengths, did show evidence for an obscured broad-line region in the near-infrared suggesting that dust extinction may play a significant role in limiting our ability to characterize the true nature of the dominant luminosity source in ULIGs. Of particular interest is whether there exists an additional population of even more heavily obscured ULIGs, which perhaps can only be penetrated at longer wavelengths.

Finally, for those ULIGs which exhibit a broad-line region at either optical or near-infrared wavelengths, the ratio of the luminosity in the broad-line $H_\beta$ emission to the total bolometric luminosity is approximately the same as that observed for optically selected UV-excess QSOs (Veilleux, Sanders & Kim 1999), suggesting that for these ULIGs the dominant source responsible for the intense infrared emission is plausibly an heavily obscured QSO.

## 4. A possible evolutionary connection between ULIGs and optically-selected QSOs

The trends of increasing AGN-dominated activity and warmer far-infrared color with merger phase observed in the RBGS and 1-Jy samples of LIGs/ULIGs (Veilleux, Kim & Sanders 1999, 2002) are consistent with an evolutionary sequence in which "cool" starburst-dominated infrared luminous galaxies transform into "warm" AGN-dominated ULIGs as the merger of two $\sim L^*$ galaxies progresses. However, the *fraction* of "cool" ULIGs which evolve into "warm" ULIGs and the subsequent *evolutionary fate* of "warm" objects has been the subject of great debate (e.g. Joseph 2000; Sanders 2000). One extreme view is that the majority, if not all, ULIGs evolve into optical QSOs: in this scenario "warm" ULIGs simply represent the initial stage in the emergence of the QSO from its dust shroud (e.g. Sanders et al. 1988).

One important test of the hypothesis that ULIGs evolve into optical QSOs is the establishment of a continuity of properties in the host galaxies of these two classes of objects. For example, the host galaxies of QSOs and ULIGs should have similar total masses. The host galaxies of optical QSOs should still show evidence of the previous merger (e.g. fading tidal debris), and perhaps the signatures of a fading circumnuclear starburst phase that peaked during the LIG phase. The strength of such features would of course depend on the timescale for the transition from the "warm" ULIG phase to the UV-excess optical QSO phase. Also, given the current extreme selection criteria – one at $60\,\mu m$ and the other using a (U-B) excess – one could reasonably expect to find a substantial number of new QSOs with "intermediate" SEDs, i.e. objects where the far-infrared emission peak $(8 - 1000\,\mu m)$ has both decreased and shifted its peak toward shorter infrared wavelengths, and which also perhaps begin to show evidence of a "big-blue-bump" $(0.1 - 1.0\,\mu m)$.

Here we simply point out that there is already a growing body of evidence in favor of the above evolutionary scenario, which leads to the suggestion that a substantial fraction of QSOs may have passed through an ULIG phase. First, elliptical-like host galaxies are common among "warm" ULIGs, and the mean R-band and K-band luminosities and half-light radii of these hosts (Veilleux, Kim & Sanders 2002) are in excellent agreement with recent quasar measurements obtained with the Hubble Space Telescope (McLeod & McLeod 2001). Second, evidence for interactions and mergers has been seen in nearby optical QSOs. The seminal paper by Stockton & MacKenty (1982) on the host galaxies of 3CR249.1 and Ton202 suggested that their host morphologies "resulted from interactions between two galaxies of roughly equal mass and that the galaxies involved possessed extensive rotating gaseous disks before their encounters". Subsequent studies of larger QSO samples illustrated the frequent occurrence of both tidal features and nearby companions (e.g. Hutchings & Neff 1992; Hutchings et al. 1994; Disney et al. 1995; Bahcall et al. 1997; Stockton 1999). Third, a subset of optically selected "infrared-excess" QSOs (e.g. Surace et al. 2001) are particularly good candidates for "transition objects" that have just gone through a ULIG phase and are in the process of becoming more like the majority of UV-excess QSOs. Canalizo & Stockton (2001) have shown that these transition-QSOs

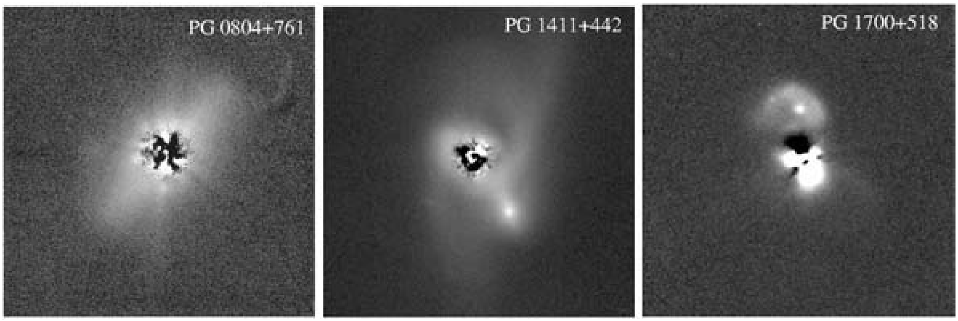

**Figure 6.** Adaptive optics H-band images of the host galaxies of three Palomar-Green Bright QSOs (Schmidt & Green 1983) imaged with the Hokupaa near-infrared camera on the Gemini-North telescope (Guyon 2002). In all three images both the central bright point source PLUS a mean azimuthally averaged radial brightness profile have been subtracted. The resulting image thus shows the non-axisymmetric brightness distribution present in the QSO host galaxy.

exhibit evidence of strong recent star-formation activity, which in most cases is directly related to a previous strong tidal interaction/merger. Evans et al. (2001) discovered large masses of molecular gas in infrared-excess QSOs, and Scoville et al. (2003) extended these results to cover QSOs with an even wider range of infrared/optical luminosity ratios.

## 5. Future work

It is clear that LIGs/ULIGs become an increasingly important class of objects at high redshifts (see Figure 1). Thus, a better understanding of the nature of the luminosity sources which power these objects is mandatory if we are to have a true picture of the cosmic evolution of superstarbursts and massive black holes.

One important project we are currently pursuing is a deep imaging study of the host galaxies of a complete sample of nearby QSOs using adaptive optics on 8m-class telescopes (Guyon et al., in preparation). Figure 6 shows an example of the psf-subtracted images, illustrating the clear presence of tidal features and disk/bar-like structures that appear to be commonplace in QSO hosts. Preliminary results from the study of all 36 QSOs shows that there is a strong correlation between the strength of the far-infrared luminosity and the strength of tidal features (arms, tails, ripples/shells, ...) in the hosts, which if true would further strengthen the case for an evolutionary connection between ULIGs and optical QSOs. A comparison with merger simulations, using both the strength of tidal debris features and the degree of relaxation of the merger remnant at large radii, allows us to make a preliminary estimate of the timescale for the total ULIG-QSO phase, which appears to be $\sim 0.6 - 1.0\,\mathrm{Gyr}$.

There is clearly a need for obtaining larger high-redshift samples of LIGs/ULIGs with well identified positions and redshifts. Until now, there is a fair degree of uncertaintly in the shape of the luminosity function with increasing redshift. Also, it is not clear if we are sampling the same or widely different source populations when combining the IRAS, ISO and SCUBA deep field sources. There are currently only a few small samples of faint ISO sources with well-identified optical/near-IR counterparts at $z > 0.5$ and the identification of optical/near-IR counterparts to the faint submillimeter SCUBA sources is still in its infancy. In the very near future, the *Spitzer* Infrared Telescope should provide relatively large samples of sources covering the full range of redshifts sampled by both the ISO and SCUBA deep fields, hopefully with sufficient positional accuracy to allow for proper source IDs and subsequent follow-up studies.

## Acknowledgements

CMI and OG acknowledge support from the Subaru Telescope operated by the National Astronomical Observatory of Japan. JMM was supported by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. JAS was supported by the Spitzer Science Center at the California Institute of Technology. Spitzer is carried out at JPL, under contract with NASA. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. JJ was supported by the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., on behalf of the international Gemini partnership of Argentina, Australia, Brazil, Canada, Chile, the United Kingdom, and the United States of America.

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