RevMexAA (Serie de Conferencias), **24**, 205–209 (2005)

COSMOLOGICAL SURVEYS WITH THE SPITZER SPACE TELESCOPE

P. G. Pérez-González,[1] G. H. Rieke,[1] E. Le Floch,[1] C. Papovich,[1] J. S. Huang,[2] P. Barmby,[2] H. Dole,[1] E. Egami,[1] A. Alonso-Herrero, [1] J. R. Rigby,[1] L. Bei,[1] M. Blaylock,[1] C. W. Engelbracht,[1] G. G. Fazio,[2] K. D. Gordon,[1] K. A. Misselt,[1] J. E. Morrison,[1] J. Muzerolle,[1] M. J. Rieke,[1] S. P. Willner,[2] and E. T. Young[1]

RESUMEN

El telescopio *Spitzer* de la NASA (antes conocido como el *Space Infrared Telescope Facility*, SIRTF), operando ya de manera normal, está abierto a propuestas de observación de la comunidad internacional. Uno de los programas de *Guaranteed Time Observer* (observadores con tiempo garantizado) consiste en una serie de exploraciones cosmológicas a través de los dos instrumentos de imagen a bordo de Spitzer: MIPS (que observa en 24, 70 y 160 micras), y IRAC (3.6, 4.5, 5.6 y 8 micras). El proyecto incluye observaciones de diversa profundidad, desde exploraciones poco profundas en campos amplios, hasta imágenes muy profundas limitadas por la confusión de fuentes. En paralelo, nuestro equipo científico está involucrado en otros programas (utilizando también datos del espectrógrafo de Spitzer, llamado IRS) que sirven de complemento y ayuda para comprender los resultados obtenidos por las exploraciones cosmológicas: por ejemplo, se está llevando a cabo una caracterización de las distribuciones espectrales de energía de aproximadamente 150 QSOs, y también se están estudiando en profundidad galaxias con formación estelar y baja metalicidad del Universo local. La primera luz del GTC está prevista justo cuando saldrán a la luz los resultados más interesantes de las Exploraciones Cosmológicas de Spitzer, lo que supondrá que GTC puede ser un telescopio ideal para estudios detallados (fotométricos y espectroscópicos) de fuentes interesantes seleccionadas en el infrarrojo medio y lejano. Si añadimos al conjunto GTC-Spitzer el *Large Millimeter Telescope* (LMT), nos encontramos con la posibilidad de estudiar muestras de galaxias muy amplias con una sensibilidad y en un rango de longitudes de onda que no tiene parangón hasta la actualidad.

ABSTRACT

NASA's Spitzer Space Telescope (formerly known as the Space Infrared Telescope Facility SIRTF) is now on normal science operation and open to the international community. One of the Guaranteed Time Observer programs consists in a series of surveys using the two imaging instruments on Spitzer: MIPS (observing at 24, 70, and 160 microns) and IRAC (3.6, 4.5, 5.6 and 8 microns). The program includes observations to various depths, from wide field shallow, to very deep confusion limited surveys. We are also conducting a series of supporting programs (including also data from the spectrograph on Spitzer, IRS) to help interpret what we see in the deep surveys, e.g., the characterization of the spectral energy distributions of about 150 QSOs, and an extensive study of low-metallicity nearby star-forming galaxies. GTC first light is scheduled when the first well-established results from our Cosmological Surveys program will be released, offering us an incomparable facility to perform spectroscopic and photometric follow-ups of mid- and far-infrared selected sources. Moreover, the combination of the GTC, Spitzer and the Large Millimeter Telescope (LMT) facilities will allow us to study the galaxy populations in the Universe with a sensitivity and a coverage of the electromagnetic spectrum that have no precedents until today.

Key Words: **COSMOLOGY: OBSERVATIONS — GALAXIES: HIGH-REDSHIFT — INFRARED: GALAXIES**

1. INTRODUCTION

How did galaxies form? How did they assemble? How did they evolve to the present? A huge effort over the past two decades has addressed these fundamental issues. Remarkable progress has been made, particularly on galaxies bright in the rest-frame ultraviolet (UV) and visible (see Ellis 1997 and Ferguson, Dickinson & Williams 2000). We have found that galaxies at high redshift often have different morphologies than the orderly Hubble sequence in the Local Universe. We have discovered different classes of object through surveys at different wavelengths: Lyman-break galaxies bright in the ultraviolet (Steidel, Giavalisco, Pettini et al. 1996), Extremely Red Objects in the near infrared (NIR, El-

[1]University of Arizona, Tucson, AZ, USA.

[2]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA.

ston, Rieke & Rieke 1988), Luminous and Ultraluminous Infrared Galaxies in the mid-infrared (Rieke & Low 1972), and objects bright at sub-millimeter wavelengths (Smail, Ivison, Blain et al. 1997). The luminosity of all these kinds of objects is dominated either by massive knots of newly-formed stars (starbursts), more or less extinguished by dust, or by mass accretion by massive black holes (active galactic nuclei, AGNs). It has become clear that making further progress requires relating these various samples to each other in a rigorous manner to place them in a broad context of overall galaxy evolution. The foremost challenge is to relate the IR/sub-mm population of luminous objects with the UV/visible ones. It appears that the two spectral ranges largely detect two distinct populations of high redshift galaxies. Each of these populations contributes roughly equally to the cosmic background luminosity, so both must be analyzed to understand the history of star formation and the evolution of galaxies.

Infrared surveys, although still in a rudimentary state compared with UV/optical ones, provide an important perspective in understanding galaxy evolution. Early ground-based photometry (Rieke & Low 1972) and the *Infrared Astronomical Satellite* (IRAS) revealed a population of massive galaxies in the Local Universe with extremely high rates of star formation ($SFR > 100\,\mathcal{M}_\odot\,\mathrm{yr}^{-1}$): the ultraluminous infrared galaxies (ULIRGs). This violent star formation is almost completely undetectable in the optical and UV part of the spectrum due to huge attenuation by dust. Together with lower-luminosity dust-embedded starbursts, this type of activity accounts for 10 to 20% of the local star formation. The *Infrared Space Observatory* (ISO) showed that these dust-enshrouded starbursts have undergone strong evolution from $z \sim 1$ to $z = 0$ (Franceschini, Aussel, Cesarsky et al. 2001). From these results and those in the sub-mm with SCUBA, it appears that the output of the ULIRGs may dominate the energy density in the Universe at z $\geq$ 1. However, ISO had severe limitations in probing the ULIRG population at z $\geq$ 1. Its FIR detectors in ISOPHOT ($50 - 120\,\mu$m) were limited in both sensitivity and number (9). ISOPHOT obtained better results at 170 μm, but its projected pixel size was large (90") and follow-up of the sources has been difficult. At $z \geq 1$, the 8 μm PAH band is shifted out of the longest ISOCAM band at 15 μm. Thus, we know little about the ULIRG population at $z = 1 - 2$, where we believe the co-moving SFR density reaches a maximum (Somerville, Primack, Faber et al. 2001; Lanzetta, Yahata, Pascarelle et al. 2002), most of the stars in galaxies were formed (Dickinson, Papovich, Ferguson & Budavári 2003; Calura & Matteucci 2003), and dynamic structures, like bars and disks, start to have a role in galaxy evolution (Mo, Mao & White 1998).

2. THE MIPS GUARANTEED TIME OBSERVER (GTO) PROGRAM

Spitzer has a band at 24μm, which will encompass PAH emission to $z > 2$ (Figure 1).The sensitivity of this band is an order of magnitude greater than the ISO 15$\,\mu$m band, and 16 times as many pixels. Early shallow surveys of small regions on the sky have resulted in detection of at least two dozen galaxies at $z > 1$ and half a dozen (generally associated with SCUBA sources) at $z > 2$ (all with $R > 22.5$). *Spitzer* also has bands at 70 and 160 μm, with similar gains over ISO to those at 24μm. The majority of the $z > 1$ galaxies are detected in one or both of these FIR bands. *Spitzer*, and particularly its **MIPS instrument, provides for the first time the ability to survey large fields on the sky to adequate depth to resolve the majority of the FIR background and to characterize the $z \geq 1$ population of ULIRGs and starbursts.** Moreover, MIPS provides a link between the population of objects being discovered in the sub-mm and mm and the UV/optical/NIR wavelengths, giving us a key new tool to understand galaxy evolution.

The other imaging instrument on Spitzer, IRAC, observing at 3.6, 4.5, 5.6, and 8 μm, has also a high sensitivity, being perfect for probing the NIR rest-frame wavelengths (and, thus, the stellar mass) at several redshifts in the range $0 < z < 3$. Indeed, IRAC easily gets to the same sensitivity of ground-based K-band surveys, given that Spitzer gets rid of the atmospheric emission (see Figure 1).

3. PRELIMINARY RESULTS

Our *Spitzer* GTO program (P.I. Marcia Rieke) emphasizes obtaining deep surveys of a number of carefully selected fields. In November 2003, we observed a $5.7' \times 5.7'$ region (roughly a 1% of the area that we will cover in this field, and 1/8% of the total survey) of the Lockman Hole with MIPS and IRAC, in the framework of the *Spitzer* Early Released Observations. We supplemented these observations with ancillary data such as deep optical and NIR images in the $UBVRIJHK$ broad-band filters as well as X-ray (XMM), sub-millimeter (SCUBA), millimeter (MAMBO) and radio (VLA) observations published in the literature. We describe below the first results that we derived based on the analysis of this unique dataset on several scientific topics:

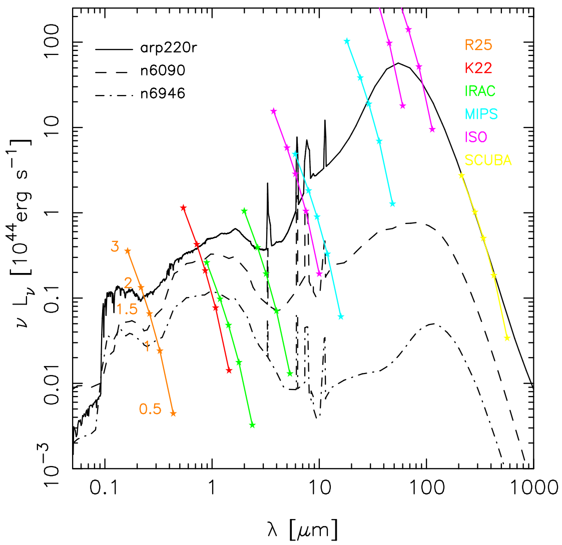

Fig. 1. Detection limits for several surveys from the R and K bands (limiting magnitudes $R = 25$ and $K = 22$) to sub-millimeter wavelengths (SCUBA). The depths of these surveys correspond to the data that the MIPS/GTO Cosmological Surveys Program already has. Three SEDs are shown for typical galaxies: a ULIRG (Arp220, $SFR \sim 300\,\mathcal{M}_{\odot}\,\mathrm{yr}^{-1}$), a starburst (NGC6090, $SFR \sim 50\,\mathcal{M}_{\odot}\,\mathrm{yr}^{-1}$), and a quiescent spiral (NGC6916, $SFR \sim 5\,\mathcal{M}_{\odot}\,\mathrm{yr}^{-1}$). The color lines represent the detection limits of the different surveys for each of the redshifts marked on the R25 line. MIPS 24 μm GTO deep survey is able to detect starbursts up to $z \sim 1.0 - 1.5$, and ULIRGs up to $z \sim 3$.

1) Luminous Infrared Galaxies at $z \geq 1$: we built spectral energy distributions (SEDs) from the U-band to the radio wavelengths for ~200 24 μm selected sources. Our analysis reveals that the combination of IRAC and NIR data is really helpful to constrain the position of the rest-frame 1.6 μm stellar bump emission, which leads to a rather accurate photometric redshift determination. This allowed us to clearly locate IR-bright (24 μm) sources at $1 < z < 2.5$ (see Figure 2). All these sources are characterized by 8-1000 μm luminosities larger than 10^{11} $L_{\odot}$. It is important to note that these high-z luminous infrared galaxies are in excess of what the prior-Spitzer models had predicted (mainly based on ISO data), and their contribution clearly appears in the 24 μm source number counts. We are now working on the detailed characterization of these sources, most of them lying at the 'redshift desert' (Steidel, Shapley, Pettini et al. 2004). With this work, we will be able to measure the evolution of luminosity and the relative roles of different activity types from

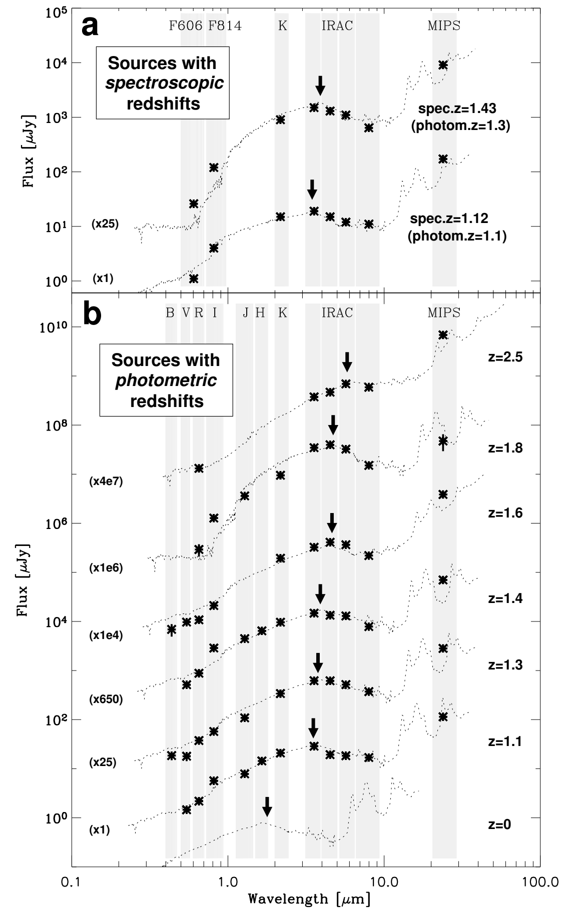

Fig. 2. This panel shows example SEDs (data points in black and model templates in gray) of some of the objects in the Lockman Hole selected at 24 μm and with photometric redshifts $z \geq 1$. The upper panel shows sources in the Groth Strip also detected at 24 μm and with spectroscopic redshift confirmation. These sources were used to test our photometric redshift technique. Redshifts are shown on the right of each object, and the 1.6 μm bump is marked with an arrow.

$z \geq 2$ to the present. We believe that this time interval encompasses the assembly of elliptical galaxies (possibly indicated by very high FIR luminosity) and the growth of spiral disks. It also extends virtually from the peak of AGN density to the present, where we live in a virtual AGN desert (see Gebhardt, Bender, Bower et al. 2000; Barger, Cowie, Bautz et al. 2001; Wyithe & Loeb 2003).

2) SCUBA/VLA/MAMBO sources: Comparison between our MIPS/IRAC data with longer wavelength observations performed from the submillimeter to the radio (e.g., SCUBA, MAMBO, VLA) shows that most of the radio sources are

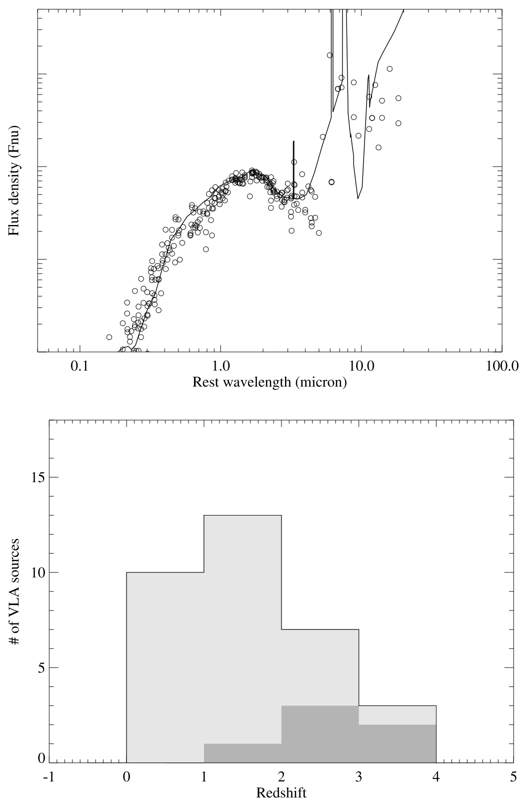

Fig. 3. The upper plot shows the average spectrum of the 24 μm selected sources in the Lockman Hole with radio detection (VLA). The spectrum of Arp220 is also depicted. The lower plot shows the distribution of photometric redshifts of this radio-FIR sample. The dark gray histogram refers to objects which were also detected at sub-mm wavelengths (SCUBA sources).

clearly detected at 24 μm independently of their potential identification with a SCUBA source. This clearly emphasizes on the ability of MIPS to unveil luminous-IR galaxies detected with the VLA but lying below the detection threshold of SCUBA, and demonstrates how MIPS will be able to accurately constrain the fraction of radio sources mainly powered by IR-luminous star-forming activity. Furthermore, we stress that more than half of the SCUBA/MAMBO sources in the Lockman Hole are detected with IRAC. Thanks to the narrow PSF characterizing this instrument, this enables a determination of their position with a much better accuracy than in the sub-mm/mm range. The IRAC photometry also provides tight constraints to determine photometric redshifts of SCUBA sources based on the stellar bump redshifted in the IRAC bands. Our Spitzer observations will therefore supplement the wealth of existent data sets targeted to these

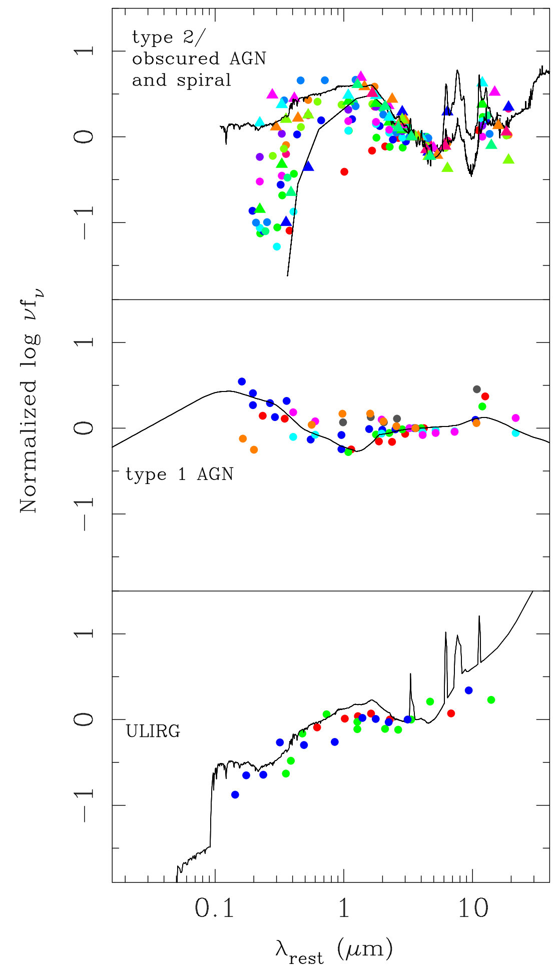

Fig. 4. Optical/NIR/IRAC/MIPS broad-band photometry of XRAY selected sources. Three types are considered: type 1 AGNs, type 2, and ULIRG-like sources. All the SEDs have been taken to $z = 0$. Typical templates are shown in each panel.

SCUBA galaxies. In particular, we will characterize more thoroughly the masses of these objects by sampling with IRAC their rest-frame K-band stellar emission, as well as their instantaneous star formation rate and their hot dust content with combination of emission-line (obtained with 10 m telescopes) and 24 μm observations (Figure 3).

3) X-ray sources: a similar analysis was performed based on the 24 μm versus X-ray correlations. We found a proportion of ∼50–65% sources detected both in the mid-infrared and the X-rays, and those exhibit a broad diversity of SEDs including type 1, type 2 and obscured AGNs as well as starburst and normal spiral galaxies. Yet, the crucial issue of their redshifts is still lacking to us. Contrary to what we found for the classical starburst galaxies, the optical/infrared SEDs that we obtained for many of the X-ray sources do not show any obvious spectral feature to determine a photometric redshift. This drawback is commonly encountered for AGNs, and stresses the need for spectroscopic redshifts. Furthermore, our first analysis reveals a surprising lack of correlation between the observed X-24 μm ratio and the other features such as the X-ray hardness. Obtaining optical/NIR spectra will be a critical step in better understanding the physical properties of these objects (Figure 4).

4. THE RELEVANCE OF GTC AND ALMA

Some of the fields observed by our GTO Cosmological Surveys program are already among the ones selected by projects linked to the GTC. This is the case, for example, of the Groth Strip, which is one of the main fields where the GOYA (Galaxy Origins and Young Assemblies) project will use EMIR for getting NIR spectra of $0 < z < 3$ galaxies. It will be very interesting to carry follow-up observations of interesting infrared-bright sources with GTC. OSIRIS will be a very useful instrument to get optical spectra of these sources, which will also allow us to measure emission-lines fluxes (such as $[OII]\lambda 3727$, $H\beta$, $[OIII]\lambda 5009$ or $H\alpha + [NII]\lambda\lambda 6548, 84$) that can be used to constrain the dust and extinction properties, to get star formation rates (complementing the FIR calculations), and to obtain estimates on the metallicity (see, e.g., Contini, Treyer, Sullivan et al. 2002). The same will be possible for the most distant sources by obtaining NIR spectra with EMIR. The imagers on GTC, CanariCam and Circe, will be perfect to get some information about the faintest (and probably most distant) objects.

All the x-ray to FIR photometric and spectroscopic data together offer an incomparable opportunity to carry out a detailed and robust study of the star formation history (reliably constrained by IR and emission-line fluxes) and mass content (traced by NIR luminosity) through stellar population modeling (Papovich, Dickinson, & Ferguson 2001; Pérez-González, Gil de Paz, Zamorano et al. 2003a; Pérez-González, Gil de Paz, Zamorano et al. 2003b) of galaxies at $0 < z < 3$.

We thank the funding from the MIPS and IRAC projects, which are both supported by NASA through the Jet Propulsion Laboratory, subcontracts #960785 and #1256790

REFERENCES

Barger, A. J., Cowie, L. L., Bautz, M. W., Brandt, W. N., Garmire, G. P., Hornschemeier, A. E., Ivison, R. J., Owen, F. N., 2001, AJ, 122, 2177

Calura, F., Matteucci, F., 2003, ApJ, 596, 734

Contini, T., Treyer, M. A., Sullivan, M., Ellis, R. S., et al., 2002, MNRAS, 330, 75

Dickinson, M., Papovich, C., Ferguson, H. C., Budavári, T., 2003, ApJ, 587, 25

Ellis, R. S., 1997, ARA&A, 35, 389

Elston, R., Rieke, G. H., Rieke, M. J., 1988, ApJ, 331, L77

Franceschini, A., Aussel, H., Cesarsky, C. J., Elbaz, D., Fadda, D., 2001, A&A, 378, 1

Ferguson, H. C., Dickinson, M., Williams, R., 2000, ARA&A, 38, 667

Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJ, 539, 13

Lanzetta, K. M., Yahata, N., Pascarelle, S., Chen, H., Fernández-Soto, A., 2002, ApJ, 570, 492

Le Fevre,O., Vettolani, G., Paltani, S., Tresse, L., et al., 2004 (astro-ph/0403628)

Mo, H. J., Mao, S., White, S. D. M., 1998, MNRAS, 295, 319

Papovich, C., Dickinson, M., Ferguson, H. C., 2001, ApJ, 559, 620

Pérez-González, P. G., Gil de Paz, A., Zamorano, J., Gallego, J., Alonso-Herrero, A., Aragón-Salamanca, A., 2003a, MNRAS, 338, 508

Pérez-González, P. G., Gil de Paz, A., Zamorano, J., Gallego, J., Alonso-Herrero, A., Aragón-Salamanca, A., 2003b, MNRAS, 338, 525

Rieke, G. H., Low, F. J., 1972, ApJ, 176, 95

Smail, I., Ivison, R. J., Blain, A. W., et al., 1997, ApJ, 490, L5

Somerville, R. S., Primack, J. R., Faber, S. M., et al., 2001, MNRAS, 320, 504

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

Steidel, C. C., Shapley, A. E., Pettini, M., Adelberger, K. L., et al., 2004, ApJ (astro-ph/0401439)

Wyithe, J. S. B. & Loeb, A., 2003, ApJ, 595, 614

A. Alonso-Herrero, L. Bei, M. Blaylock, H. Dole, E. Egami, C. W. Engelbracht, K. D. Gordon, E. Le Floch, K. A. Misselt, J. E. Morrison, J. Muzerolle, C. Papovich, P. G. Pérez, G. H. Rieke, M. J. Rieke, J. R. Rigby and E. T. Young: University of Arizona, Steward Observatory, 933 N Cherry Av., Tucson, AZ85721, USA (pgperez@as.arizona.edu).

P. Barmby, G. G. Fazio, J. S. Huang and S. P. Willner: Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA.