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EXPLOITATION OF CANARICAM: OPENING NEW WINDOWS FOR SPANISH ASTROPHYSICS

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RESUMEN

CanariCam es el instrumento de imagen directa infrarroja de Día 1 del Gran Telescopio Canarias (GTC) de 10 m. Sus opciones multimodo que permiten la realización de espectroscopíam polarimetría y coronagrafía harán que CanariCam sea el instrumento del infrarrojo medio más avanzado y versátil del mundo. Como tal, CanariCam ofrecerá una serie de opciones a la comunidad científica española que jamás han tenido antes. CanariCam tiene unas prestaciones que son por lo general superiores a *ISO*, sobre todo en la resolución espacial, y permitirá a los científicos españoles realizar nuevos proyectos en muchos campos distintos de la astrofísica. Este artículo describe algunas de las opciones que ofrece Canaricam para realizar una ciencía de vanguardia.

ABSTRACT

CanariCam is the Day One mid-infrared imager for the Spanish 10 m Gran Telescopio Canarias (GTC). With its multimode options that allow spectroscopy, polarimetry, and coronography, it will be the most advanced and versatile mid-infrared instrument available to astronomers. As such, CanariCam will offer the Spanish scientific community a range of options that have never previously existed. CanariCam will offer capabilities that are generally superior to those of *ISO*, particularly in spatial resolution, and will permit Spanish scientists to carry out new and exciting science projects in many fields. This paper describes some of the possibilities that Canaricam offers for original science.

Key Words: **INFRARED : GENERAL — INFRARED : ISM — INFRARED : SOLAR SYSTEM INFRARED: SOLAR SYSTEM — INFRARED: STARS — INSTRUMENTATION : GENERAL**

1. INTRODUCTION

CanariCam is designed and optimized as a diffraction-limited imager. At 8 μm it will give a resolution of $0.18''$, this may though be bettered by using image improvement techniques, given the stability of the point spread function (PSF) of the instrument. However, CanariCam is provided with additional observing modes that give it a great versatility. Apart from direct imaging, CanariCam will be able to observe in spectroscopic mode (with high ($R \sim 1000$) and low ($R \sim 100$) resolution capability in both the 10 and 20 μm windows), imaging polarimetry, and coronography. A detailed description of CanariCam and its capabilities is given by Telesco (this volume, p. 19).

One of the key scientific opportunities presented by CanariCam is its capability to penetrate dust very deeply. (Rieke 1985) present an interstellar extinction law to 13 μm which shows that the extinction in the ISM at this wavelength is $<3\%$ the extinction at V, although 8 μm in the wings of the strong 10 μm silicate feature it is as low as 2%. This allows CanariCam extremely deep dust-penetrating ability, particularly in the 20 μm window. CanariCam will thus be able to observe deeply embedded sources that are not visible to other techniques, such as star formation, the Galactic Centre and the nuclei of AGN. CanariCam will be the first dedicated mid-infrared instrument available to the Spanish scientific community and will thus open a whole new observing window for Spanish astrophysics.

1.1. *Comparison with* ISO

The *ISO* satellite has set the benchmark for mid-infrared instrumentation. A key point of comparison is that *ISO* was a 60 cm telescope and thus its spatial resolution was limited to $3.2''$ at 8 μm, a factor of 17 poorer than the CanariCam + GTC combination. CanariCam will thus be able to follow up observations of *ISO* targets with much higher spatial resolution. The expected sensitivity of CanariCam is similar to or slightly better the measured *ISO* sensitivity (Cesarsky et al. 1996). Sources may be extracted from ISOCAM data down to a limiting flux of $\approx$60 μJy (Pierre et al. 1996) for a 1σ limit. The

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TABLE 1

A COMPARISON OF SOME PROPERTIES OF ISO AND CANARICAM + GTC

Property	CanariCam	*ISO*
Detector size	320×240	32×32
Sensitivity (10 μm)[a]	0.9 mJy	
Spatial resolution (8 μm)	$0.18''$	$3.2''$

[a] 5σ in 100 s.

predicted limit for a CanariCam deep integration is $\approx$50 μJy for a 3σ detection in 4 hours (Kidger 2002). CanariCam offers a slightly higher spectroscopic resolution than *ISO* at 10 μm and coronagraphic and polarimetric modes that were either unavailable (the former) or not fully implemented on *ISO* (the latter).

1.2. *An example of the potential of CanariCam*

An example of the power of CanariCam is shown by the results obtained by its precursor instrument, OSCIR on Keck II. A study of the protoplanetary disk of HR 4796A reveals a bi-lobate structure (Telesco et al. 2000). This structure, though, is not resolved in similar observations with OSCIR on the 4 m telescope at Cerro Tololo Interamerican Observatory (CTIO[1]). Such structures may reveal the presence of already formed planets in the system (Wyatt et al. 2000).

With the CanariCam + GTC combination a resolution of 8 AU will be attained at 8 μm at 50 pc. Fainter and more distant disks can be resolved than are observable with 4 m class telescopes. It is also possible to look for grain morphology changes that may be caused by annealing of the dust grains closest to the central star (Wooden 2002).

1.3. *The potential of the GTC site for mid-IR observations*

The effectiveness of a mid-infrared instrument depends critically on the quality of its site. Measurements of water vapor at the GTC site have been carried out since 1996. Results show that $\sim$10% of nights have water vapor < 1 mm and that the median water vapor at the site in winter condition is $\sim$2 mm. CanariCam will thus be a highly competitive instrument able to work in the 20 μm window and in the wings of the 10 μm window. The capability of queue scheduling on the GTC will allow CanariCam to take full advantage of the very best conditions, which are evenly distributed round the year.

[1] See http://www.iac.es/proyect/CCam/ for a comparison of the images from Keck II and CTIO.

2. CANARICAM SCIENCE

2.1. *Overlap with OSIRIS and EMIR*

OSIRIS and EMIR are focused instruments for the GTC. OSIRIS will be a Day One visible instrument alongside CanariCam (Cepa et al., this volume, p. 13), while EMIR is planned for Day Two and will offer exceptional capabilities in the near infrared (Garzón et al., this volume, p. 23).

2.1.1. *OSIRIS*

OSIRIS may be considered a "star formation machine", whose capabilities and science program are adapted to problems of stellar formation in external galaxies (**?**). As such, there is an important overlap between the aims of OSIRIS and the capabilities of CanariCam. Some examples are:

- CanariCam offers the capability of deep penetration into regions of star formation and allows high spatial resolution of the process of star formation in both the Milky Way and nearby external galaxies.
- CanariCam offers two powerful star formation tracers that are complementary to the capabilities of OSIRIS
  - Dust emission beyond 20 μm.
  - IR hydrogen lines with low line of sight extinction.
- The tracing of magnetic fields with high resolution imaging polarimetry. What role does the B-field play in star formation?

2.1.2. *EMIR*

EMIR is designed as a "cosmology machine" for observing galaxies at high redshift (Balcells, this volume, p. 71). This gives it important areas of research overlap with CanariCam to complement its research with mid-IR data.

- The most efficient cosmological star formation tracer are the hydrogen lines.
  - Line ratios (e.g., Hα/Hβ, Paα/Paβ) give the extinction within the galaxy.
  - The main near-IR lines shift to the mid-IR at moderate and high z
    - At $z = 1$, Br$\alpha \rightarrow 10$ μm window.

- At $z = 2$, Brα & Br$\beta \rightarrow 10\ \mu$m window.
- At $z = 4$, Pa$\alpha \rightarrow 10\ \mu$m window.

For a complete understanding of star formation and its environment over the history of the Universe it is necessary to use the GTC + OSIRIS + EMIR + Canaricam combination.

2.2. *CanariCam science opportunities for the Spanish astrophysical community*

2.2.1. *Solar system*

Io CanariCam will offer opportunities for Spanish astrophysicists to enter areas of research that have previously been closed to them. One such case is planetary studies. Active vulcanism on Io was first detected during the Voyager 1 flyby in 1979 (Strom et al. 1979), and it was rapidly realized that these may also be detected from the ground in the mid-infrared (Witteborn et al. 1979). A total of 61 centers of active vulcanism have been detected by ground-based observations and space probe encounters (Lopes-Gautier et al. 2002). Major eruptions may double the observed flux at 5 μm (Spencer & Schneider 1996), with blackbody emission from 450 to 1550 K, peaking from 6.4 to 1.9 μm respectively, but lower temperature hot-spots also exist. CanariCam will have sufficient resolution at 8 μm to resolve and locate centers of activity. Measures with narrow band silicate filters will allow the variations of temperature in different activity centers to be tracked as well as revealing details of what are assumed to be silicate eruptions additional to the more typical sulfur-based activity.

Comets There is an important connection between studies of cometary dust and studies of protoplanetary disks (Wooden 2002). This impinges on various lines of Spanish research that have been important in recent years. Cometary dust shows major silicate features in both the 10 and 20 μm window that are not completely understood yet due largely to lack of both S/N and resolution (Hanner et al. 1999). CanariCam will have both the sensitivity and the resolution to attack these problems, and its entry in service coincides with the expected appearance of the bright comet C/2001 Q4 (NEAT) that will allow many important advances made in the study of silicate emission of comets based on C/1995 O1 (Hale–Bopp) and C/1996 B2 (Hyakutake) to be followed up.

A second key area to be investigated with Canaricam is the diameter of the nuclei of comets. Although estimates have been made for many comets (Fernández et al. 1999; Tancredi et al. 1996), only for 1P/Halley (Keller et al. 2002) and 19P/Borrelly (Soderblom 2001) is the diameter known from direct observation. For C/1995 O1 (Hale–Bopp) the radius estimated by different techniques ranges from 15 to 65 km (Weaver & Lamy 1999). The best method for calculating the size is thermal IR observations of bare (inactive) nuclei at large heliocentric distances. Estimates of the flux at 20 μm suggest that the emission would be easily detectable from Comet Hale–Bopp (0.9 mJy at 17 AU) and other, smaller, cometary nuclei.

2.2.2. *Extrasolar planets*

One of the most exciting and important problems in modern astrophysics, and one in which Spanish researchers have been to the fore, is that of the detection of extrasolar planets. The first accepted detection was made around 51 Peg (Mayor & Queloz 1995). The existence of extrasolar planets can now be regarded as completely secure (Marcy & Butler 2000). CanariCam can be thought of as a "planet machine" as its characteristics are ideally suited to this end. If we take a solar-type star at 10 pc, with an orbiting "jupiter", the visible magnitude of the primary and planet would be $V = 4.8$ and $V = 24.8$ respectively. The contrast between the primary and planet would be 10^8 and the separation of the two $1.0''$. No ground-based instrument could resolve the two. In the mid-IR, though we are close to the peak blackbody emission for the planet and moving away from the peak for the primary, thus the contrast is greatly reduced. At 10 μm, the contrast is 10^5, and the system could theoretically be resolved using coronography. At 25 μm, the contrast is 10^2, and the flux from the planet could be detected with CanariCam + GTC in < 500 s, with the planet clearly resolved from the PSF of the primary. Using the spectroscopic option, the atmosphere of detected objects can be analyzed in detail and its composition determined (Charbonneau et al. 2002).

CanariCam + GTC thus has a huge potential as a planet detector. Solar-type stars could be surveyed to $\approx$15 pc for Jupiter-type planets. More distant planets could be detected around hotter stars at even larger distances from the Sun because the contrast would be even lower. This is likely to be a fundamental research project with CanariCam in the first years of operation of the GTC that offers exceptional returns.

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2.2.3. *The Galactic Center region*

The nature of the central source of the Galaxy, Sgr A* has been debated for some 25 years. It is suspected to be a black hole of $\approx 10^6\ M_\odot$ (Ghez et al. 1998), but the difficulties of observation of this source have made it impossible to determine its exact nature. The best resolution to date in the mid-IR is 0.7″ (raw), 0.44″ (reconstructed), equivalent to a resolution of 3000 AU, obtained with SpectroCam-10 on the 5 m Hale Telescope (Stolovy et al. 1996), providing the first definitive detection of Sgr A* in the mid-IR. In contrast, in the near-IR the identification is uncertain (Eckart et al. 1995), as the suggested $K = 12.1$ (Close et al. 1995) counterpart with Sgr A* can be resolved into several sources. Which, if any, of these is Sgr A* is currently not known. To date, there is also no detection of Sgr A* at either 12.4 or 20 μm (Gezari et al. 1994; Morris et al. 2001), thus the source's energy distribution is not known.

Very high spatial resolution is required to resolve Sgr A* in the mid-IR as it is superimposed on a region of steep gradient of dust emission of unknown geometry, thus the high resolution of CanariCam + GTC offers the possibility of greatly improving our knowledge of this source and of obtaining detections at longer wavelengths that would allow the spectral energy distribution to be tested against the predictions of the accretion disk model, although it is seen that the accretion disk model predictions have considerable difficulties even with the current limits to flux (Stolovy et al. 1996). Of particular importance is to detect Sgr A* at mid-IR wavelengths outside the 10 and 20 μm silicate features to minimize the superimposed dust contribution. CanariCam + GTC will allow Spanish astrophysicists to participate in the forefront of these studies and can improve the current best resolution to ≈1000 AU in raw images and ≈500 AU with image improvement allowing the centermost regions to be resolved and measured.

2.2.4. *Galaxies*

Astrophysics in Spain has an established tradition of galaxy research. In the mid-infared the emission of normal galaxies changes from being dominated by stars to being dominated by warm dust, although the morphology of galaxies in the mid-IR is similar to that observed in the visible (Dale et al. 2000). In general, the transition comes at around 4 μm for late-type galaxies, as stellar photons are absorbed by interstellar dust and re-emitted in the infrared, while for normal early-type galaxies (E, S0, and S0a) the Rayleigh–Jeans tail of emission from cool stars dominates to 15 μm, although warm dust was detected in nuclei of early-type galaxies with *ISO* (Madden et al. 1999; Roussel et al. 2001). From 3 to 15 μm, the interstellar medium shows a series of unidentified emission bands that are generally referred to as PAHs, although this identification is still uncertain and the emission is dominated by very small grains (Helou et al. 2000).

A survey of Virgo and Coma galaxies with *ISO* showed that the mid-IR emission of late-type galaxies is not related to its star formation rate. For low or intermediate star formation rates there is a correlation of the mid-IR emission with the UV field, and where a strong UV radiation field is present the mid-IR emission decreases (Boselli et al. 1997). This is interpreted as meaning that the PAH molecules are destroyed by the UV field in galaxies with very high star formation rates (Boselli et al. 1998). The PAH emission thus gives a measure of the UV radiation field within the galaxy. In contrast, the large grains observed in the far-IR show an emission proportional to the overall interstellar radiation field. Similarly, the mid-IR flux density is a good tracer of the star formation rate in galaxies because of the emission from young star formation complexes embedded in dust (Vigroux et al. 2001). Thus by observing in the mid-IR we can obtain considerable information about the galaxy environment. It is also self-evident that the key to understanding the most distant galaxies is to understand completely the nearby galaxies that allow the best spatial and spectral resolution.

2.2.5. *AGN*

There is a long tradition of research into AGN in Spanish astrophysics and the advent of the GTC will undoubtedly impel new Spanish initiatives in the study of AGN. Two of the key topics in modern AGN research are unification models of AGN and studies of the core regions aimed at revealing the energetics and the emission mechanism that powers AGN.

Unification models of AGN The unified model of Seyferts requires a dusty or molecular ring with a diameter of a few parsecs to be positioned in front of the nucleus and the broad line region (BLR). This model is broadly supported by ISOPHOT observations (Pérez-García & Rodríguez-Espinosa 1998).

ISOPHOT-S spectra of a sample of CfA Seyferts show that the PAH emission is isotropic, and that Seyfert 1s have higher luminosities than Seyfert 2s (Clavel et al. 2000). However, there are several observations that conflict with this model. A statistical study of photometry between the near-infrared and the *IRAS* bands suggests the observed spectral energy distributions (SEDs) and degree of anisotropy observed in Seyfert galaxies are inconsistent with many models of dusty tori, particularly very thick and compact tori (Fadda et al. 1998). It is also notable that there is extended mid-IR emission over a ∼70–140 pc region in NGC 1068, the one Seyfert that can be well-observed with medium-sized telescopes and no point source that emits as much as 40% of the radiation (Cameron et al. 1993). *HST* observations of a sample of nearby Seyfert 2 galaxies also show that the optically bright nucleus amounts to only 1–10% of the UV flux (Close, McCarthy, & Melia 1995). This UV flux is dominated by emission from clusters of hot, young stars, with only a small contribution from the nuclear ionizing source, clearly discordant with the unified model unless the nuclear source is heavily extinguished.

There are two generic models to explain the results for Seyfert 2 nuclei: that they are obscured Seyfert 1s, or that they are high metallicity young stellar clusters. While some authors suggest that the AGN is the final stage of a nuclear starburst in which a black hole is formed (Shapiro & Teukolsky 1985), others invoke stellar evolution in a star cluster (Terlevich et al. 1992). The Hα luminosity is consistent with either model (Close, McCarthy, & Melia 1995), but PAH line strengths could be used as a test of models (Cameron et al. 1993). High resolution imaging of the central regions of AGN with CanariCam + GTC would offer temperature mapping and can differentiate between torus models, giving valuable clues as to the structure and nature of the central regions.

Dragons or warmers? CanariCam + GTC will also be able to distinguish between the models of AGN emission. The line ratios for the [Ar III], [S IV], and [Ne II] lines at 9.0, 10.5, and 12.8 μm are sensitive probes of the hardness of the radiation field and thus of models (Laurent et al. 2000). If the ionizing source is a warmer (Terlevich et al. 1992), the ionizing field would be relatively soft, with a relatively small high energy component. In contrast, a black hole (Shapiro & Teukolsky 1985) would give a much harder field. These lines are too weak to be detected with 4 m class telescopes. *ISO* observations of the lines suffered from the very low resolution of the CVF of ∼40 (Laurent et al. 2000). CanariCam + GTC offers both a better low resolution in 10 μm than *ISO* ($R \approx 100$) and the possibility of high resolution imaging in a suite of narrow band filters tuned to [Ar III], [S IV], and [Ne II] and also PAH filters that will allow the radiation field to be mapped in detail. CanariCam + GTC will allow fundamental advances in this field.

3. CONCLUSIONS

The CanariCam + GTC combination offers many exciting new areas of research for astrophysics in Spain. This paper has shown just a few of the possible applications to current Spanish research programs that will be possible with the very best ground-based mid-infrared telescope + instrument combination available in the world.

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