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Letter to the Editor

# The first ISO ERO: A dusty quasar at $z = 1.5$*

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**Abstract.** We report the discovery of an extremely red object (ERO) in a medium-deep ISOCAM extragalactic survey. The object is also a radio source. Subsequent VLT NIR spectroscopy revealed a prominent H$\alpha$ line giving a redshift of 1.5. We present the spectrum and photometric data points and discuss evidence that ISO J1324−2016 is a quasar harbouring a significant amount of very hot dust.

**Key words.** infrared: galaxies – quasars: general – galaxies: starburst – quasar: individual: ISO J1324−2016

## 1. Introduction

In the course of the ISOCAM Core Programme devoted to the observation of $z \sim 0.2$ galaxy clusters (DEEPXSRC), we have discovered a faint field source at 7.5 and 15 $\mu$m with no obvious counterpart on medium deep optical images. This object was thus a *potential* "extremely red object" (ERO), but *for the first time*, being directly unveiled through mid-infrared (MIR) observations. The new ERO class, usually defined by $R - K > 5$ or $R - K > 6$, is not only rapidly growing in size but also in astrophysical relevance. Indeed, it may shed light on the still hotly debated question of AGN/starburst connections, the formation epoch of ellipticals as well as the existence of dust within the crucial redshift range $1 < z < 3$. For an up-to-date review on the ERO topic, see for instance Liu et al. (2000). Here, we describe the follow-up observations we have undertaken in order to determine the redshift and to shed light on the nature of this peculiar object. The next section presents the spectroscopic and photometric data from X-ray to radio wavelengths. Section 3 discusses possible interpretations in conjunction with information provided by galaxies and other EROs at comparable redshift. Throughout the paper, we assume $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$.

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* Based on observations collected at the ISO Observatory, Canada-France-Hawaii Telescope, Australia Telescope Compact Array, UKIRT, ROSAT and the European Southern Observatory (prg: 58.E-0885, 61.B-0369, 265.B-5005).

## 2. The data set

*ISO data*

The ISO observations of A1732 ($z = 0.193$) were performed in February 1996 and preliminary results are described in Pierre et al. (1996). The data have since been reprocessed, following the method presented by Fadda et al. (2000), based on extensive simulations (addition of faint sources to the science images). This provides the flux reconstruction factors, which are observation dependent, as well as error estimates, given here at the 1$\sigma$ confidence interval. Results for source ISO J1324−2016 are given in Table 1. The flux densities are below 1 mJy, which explains why ISO J1324−2016 does not appear in the IRAS Faint Source Catalogue at any wavelength. ISO J1324−2016 is identified as source 2 in Fig. 1 of Pierre et al. (1996).

*Radio data*

The cluster A1732 was observed with the Australia Telescope Compact Array (ATCA) on 1995 April 18 at frequencies of 1.344 and 2.378 GHz. Total integration time was 10 hours in the 6C array, which gives interferometer spacings from 153 m–6 km. The synthesised half-power beamwidths at the declination of A1732 were $16.8'' \times 6.8''$ (PA 1.4°) at 1.344 GHz and $9.6'' \times 4.1''$ (PA 2.3°) at 2.378 GHz. The primary flux density calibrator was PKS B1934−638, with B1245−197 and B1622−297 as secondary phase calibrators. ISO J1324−2016 appeared as an unresolved radio source, with a fitted position of 13 24 45.67 ± 0.03, −20 16 11.3 ± 0.5 (J2000), and flux densities of 1.4 ± 0.12[1] and 0.8 ± 0.1 mJy at 1.344 and 2.378 GHz, respectively. The spectral index over this interval is $\alpha = -1.0$ ($S_\nu \propto \nu^\alpha$). The $0.5''$ radio positional

[1] The value quoted in Pierre et al. (1996) is incorrect.

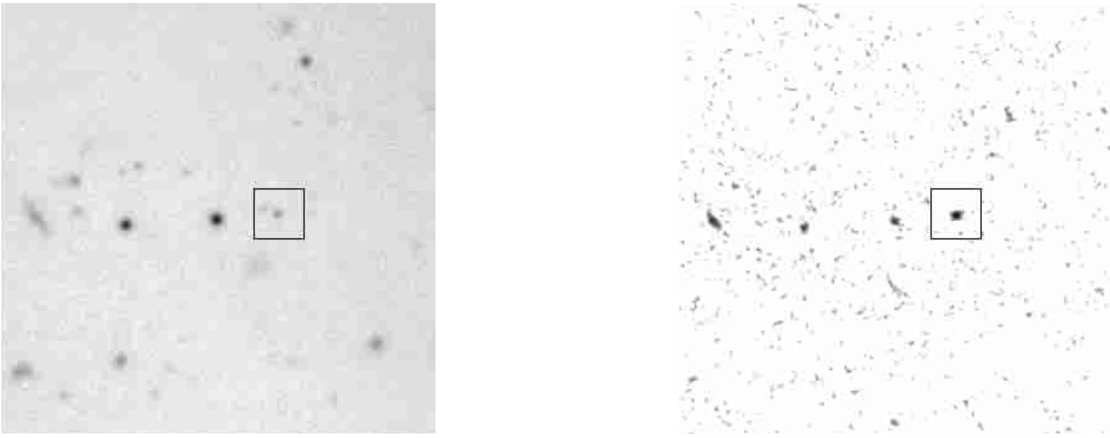

**Fig. 1.** Finding charts for ISO J1324−2016. The images are 45″ on a side; North is up, East is left. *Left*: ESO NTT/SUSI $I$ image (exp. time: 1800 s). *Right*: ESO VLT/ISAAC $K$ acquisition image (exp. time: 40 s).

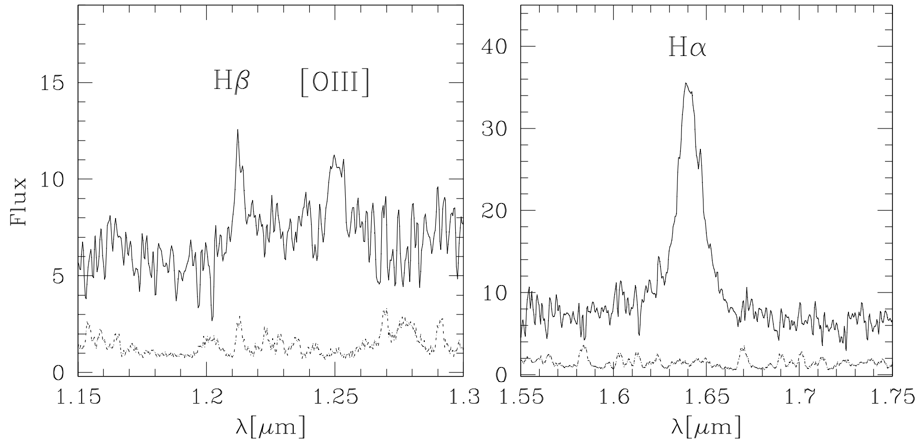


**Fig. 2.** *Right:* portion of the ISAAC $H$-band spectral interval showing the Hα line at a redshift of 1.50. The original spectrum has been lightly filtered by a Gaussian with a $\sigma$ of 1 pixel (3.6 Å). Intensity is in arbitrary units. *Left:* portion of the ISAAC $J$ spectral interval containing the Hβ and [O III] lines. No line is detected in the $K$-band spectrum. In each panel, the lower curve is the noise spectrum extracted from the same data.

**Table 1.** Photometry of ISO J1324−2016. $B$, $R$, $I$ & $K$ flux densities have been corrected for galactic extinction (NED).

| Observed Wavelength | Rest Wavelength | Flux Density | Telescope/ Instrument |
|---|---|---|---|
| $B_J$ 0.44 $\mu$m | 0.176 $\mu$m | <0.98 $\mu$Jy | CFHT (1993) |
| $R_J$ 0.70 $\mu$m | 0.28 $\mu$m | <2.8 $\mu$Jy | CFHT (1993) |
| $I_J$ 0.90 $\mu$m | 0.36 $\mu$m | 3.0 ± 0.3 $\mu$Jy | NTT/SUSI (1997) |
| $K_J$ 2.2 $\mu$m | 0.88 $\mu$m | 67 ± 6 $\mu$Jy | UKIRT (1998) & VLT/ISAAC (2000) |
| LW2 6.75 [5–8.5] $\mu$m | 2.7 $\mu$m | $0.89^{+0.47}_{-0.33}$ mJy | ISOCAM (1996) |
| LW3 15 [12–18] $\mu$m | 6.0 $\mu$m | $0.76^{+0.87}_{-0.40}$ mJy | ISOCAM (1996) |
| 13 cm | 5.0 cm | 0.8 ± 0.10 mJy | ATCA (1995) |
| 22 cm | 8.9 cm | 1.4 ± 0.12 mJy | ATCA (1995) |
| 35 cm | 14.2 cm | <2.1 mJy | MOST (1993) |

accuracy was essential for the follow-up identification work.

*Optical/NIR broad-band imaging*

From 1993 CFHT images of A1732, the following upper limits on ISO J1324−2016 were set: $B > 24.5$, $R > 22.7$. However, since the source was close to the CCD edge, and affected by vignetting, these limits do not provide a useful constraint. The source was then observed in 1997 (March 05–06) at ESO with NTT/SUSI for two hours in the $I$ band; the seeing was 0.6″. In the radio error box, we discovered an object with $I = 22.4 \pm 0.1$ (see Fig. 1). The $I$ image of the identification is unambiguously pointlike ($FWHM < 0.6''$). Subsequently, we obtained a UKIRT service image (1998 April 21) of the field and measured a $K$ magnitude of 17.5. This magnitude of $K = 17.5 \pm 0.1$ was later confirmed by the VLT/ISAAC acquisition image (see Fig. 1); moreover, with a seeing of $0.4''$, the ISAAC $K$ image of ISO J1324−2016 remains pointlike. The $I-K$ color of 4.9 emphasises the extreme redness of the source spectrum – at least in the observed frame – and the present lower limit, $R-K > 5.2$, reinforces the status of ISO J1324−2016 as an ERO.

*X-ray observations*
The field of Abell 1732 was observed with the ROSAT HRI for ∼30 ks (1996 January 15–27; Pierre et al. 1996) and with ASCA for a total integration time of ∼90 ks and ∼100 ks by the SIS and GIS instruments respectively (1997 July 6–7; Pierre et al. 1999). ISO J1324−2016 is not detected by the HRI. This sets a $3\sigma$ flux upper limit of $\sim 2 \times 10^{14}$ erg s$^{-1}$ cm$^{-2}$ in the [0.1–2.4] keV band, assuming a standard power-law spectrum with a photon index of 2 (or $4 \times 10^{14}$ erg s$^{-1}$ cm$^{-2}$ if corrected for Galactic absorption). In the [0.4–10] keV ASCA images, because of the large instrumental point spread function, the cluster image encompasses the ISO J1324−2016 position, making its detection impossible.

*The NIR spectroscopy*
A 2-hour spectroscopic observation (1998 May 23) at intermediate resolution with EFOSC on the ESO 3.6-m telescope over the range 4000–9000 Å did not reveal any significant absorption/emission features. This stressed the need for deep NIR spectroscopy with a larger telescope. ISO J1324−2016 was observed with the low resolution spectroscopic mode of VLT1/ISAAC on 2000 June 7 & 9. Three grating settings were used to cover the 1.1–2.5 $\mu$m range. As is standard in the IR, the target was observed at two positions along the slit (which we shall call the A and B beams). The bright and variable night sky lines were removed by subtracting the respective spectra from each other. The resulting two-dimensional spectra were then corrected for slit distortion and wavelength calibrated with the OH lines or with arc lamps. Residual lines from the night sky were then removed by combining spectra from the A and B beams. This process works well enough that one-dimensional spectra can be extracted without any need for additional sky subtraction. In addition to ISO J1324−2016, two hot stars, with spectral type A0 or earlier, were observed with the same instrument configuration. These stars were used to remove telluric features in the spectra of ISO J1324−2016. The one-dimensional spectra are shown in Fig. 2; spectral resolution is 21.4 and 28.4 Å in the $J$ and $H$ bands respectively. The redshift from the H$\alpha$ line is $1.500 \pm 0.002$. The H$\beta$ and [O III] lines show a relative blueshift of some 1500 and 800 km s$^{-1}$ respectively. The Balmer decrement is uncertain because the H$\beta$ line is very noisy (due to a sky line at 1.215 $\mu$m) and appears to be narrower than H$\alpha$; the estimated value of $20^{+10}_{-4}$ is significantly higher than more common values of 5–10. The total corresponding $B$ extinction would be $A_B = 7^{+2}_{-1}$ in the source restframe, assuming standard extinction laws (Mathis 1990).

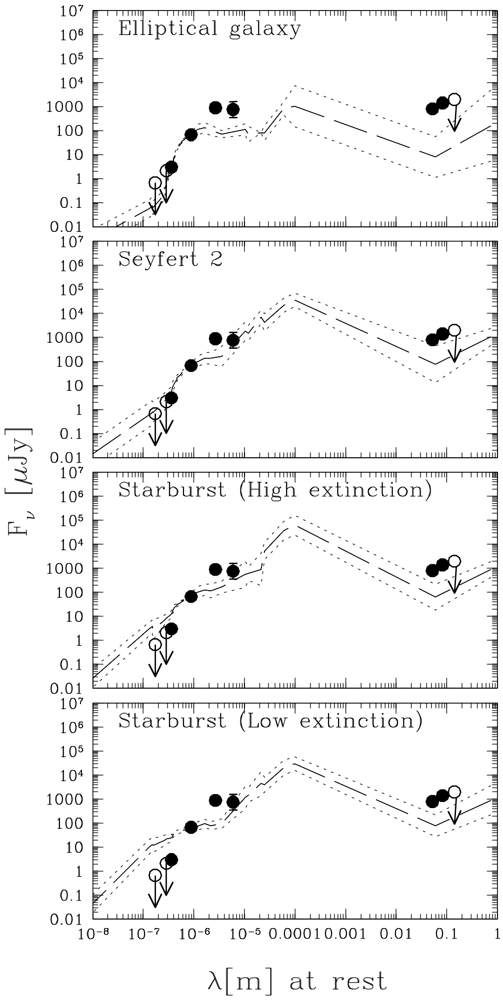


**Fig. 3.** Rest frame spectral energy distribution (SED) of ISO J1324−2016 (filled circles) compared with typical local galaxy SEDs from Schmitt et al. (1997). The template spectra have been normalised to the $K$ magnitude point. The dashed line is the averaged SED and the dotted line gives the observed $1\sigma$ dispersion. Open circles are upper limits. The average SED of spirals appears to be quite similar to that of ellipticals and thus is not presented here. The radio data do not constrain the optical-MIR SED but are shown here for completeness.

## 3. Discussion

We note first that, although ISO J1324−2016 is in the field of A1732, it is certainly not a lensed object (at least in the strong regime), since it is located 0.8 Mpc ($4.8'$) in projected distance from the cluster centre. The VLT/ISAAC spectrum unambiguously demonstrates that ISO J1324−2016 is powered by an active nucleus, a fact already suggested by its pointlike appearance in the $I$ and $K$ bands, together with its radio activity. The H$\alpha$ $FWHM$ (∼3000 km s$^{-1}$) and rest frame equivalent width (300 Å) are very similar to those seen in other high redshift quasars (Espey et al. 1989). We now consider the $R$, $I$ & $K$ photometry, which defines ISO J1324−2016 as an ERO. With a $K$ magnitude of 17.5, ISO J1324−2016 is brighter than most EROs but fainter than known quasars

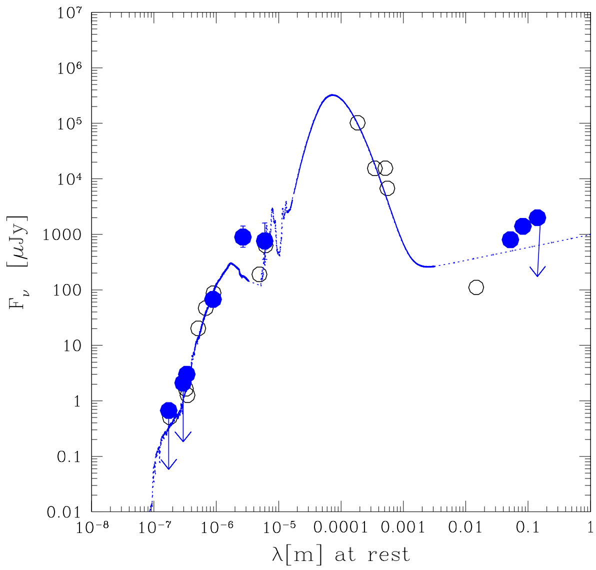


**Fig. 4.** Rest frame SED of ISO J1324−2016 (filled circles) compared with the strong starburst HR10 (open circles), an ERO with a similar redshift. The HR10 spectrum (Elbaz et al. 2001) has been normalised by a factor 2.4 in order to match the observed $K$ magnitude of ISO J1324−2016. The line shows the best fit to the HR10 points assuming a pure starburst model, constrained particularly in the MIR range by the ISOCAM CVF dataset on local galaxies (Chanial 2001). No LW2 (5–8.5 $\mu$m) value is available for HR10; instead, LW10 (8–15 $\mu$m) was obtained. Note that the well known weak 3.3 $\mu$m (rest frame) PAH line marginally affects the LW2 band, whereas it is fully encompassed by the LW10 band.

at a similar redshift (Wright et al. 1983; Falomo et al. 2001). Comparison with local templates (Fig. 3) shows that, on the basis of these colours alone: (i) the pure starburst hypothesis seems unlikely, and (ii) ISO J1324−2016 is compatible with either an elliptical or a Seyfert 2 galaxy at a redshift of 1.5. On the other hand, the ISOCAM data points clearly exclude a normal elliptical galaxy. These two MIR values are likely to have different origins: between 5–16 $\mu$m (rest frame), MIR emission in galaxies is due mainly to black-body radiation from the photospheres of the evolved stellar population and/or dust heated either by stars or an active nucleus. The fact that in ISO J1324−2016 the 2.7 $\mu$m (rest frame) flux is significantly higher than that of a standard Seyfert galaxy suggests the presence of an additional hot component. Indeed, the excess from 1–3 $\mu$m, can naturally be explained by very hot dust emission in the circumnuclear region of an AGN (e.g. Kobayashi et al. 1993). These grains can reach temperatures of a few thousand degrees before they sublimate. In addition, we have compared ISO J1324−2016 with another ERO, for which ISOCAM photometry is also available (Fig. 4), namely HR10, "a distant clone of Arp 220" at $z = 1.44$ (Elbaz et al. 2001). In HR10 the bulk of emission at 15 $\mu$m appears to be related to star formation rather than to the presence of an active nucleus with a hot dust component. Again, the two objects show very similar SEDs between the observed $I$ and $K$ bands. Furthermore, this comparison extends to 15 $\mu$m, but not around the 7.5 $\mu$m point which appears significantly higher for ISO J1324−2016. This supports the previous evidence that the emission process is much more energetic in ISO J1324−2016, consistent with the presence of a powerful central engine. From the radio data, we find a total intrinsic power of $P_{1.4\,\mathrm{GHz}} = 1.9 \times 10^{25}$ W Hz$^{-1}$ (rest frame), using the spectral index of −1 derived from the 20 and 13 cm measurements. This places ISO J1324−2016 within the Fanaroff & Riley (1974) break range $P_{1.4\,\mathrm{GHz}} \sim 10^{24} - 10^{26.5}$ W Hz$^{-1}$, shown to be a strong function of the absolute isophotal magnitude of the galaxy by Ledlow & Owen (1996). Our current limit on the radio angular size of ISO J1324−2016 is compatible with the source falling into the class of compact steep-spectrum quasars. The NIR spectrum of ISO J1324−2016 shows some obvious similarities to that of the ultra-steep-spectrum red quasar WN J0717+4611 at $z = 1.462$ (de Breuck et al. 1998), particularly in regard to the line ratios. The latter object is polarized, and the authors argue that the origin of the polarization is scattering by small dust grains or electrons. Indeed, the presence of dust appears to be common in radio-loud quasars, with the extinction being a function of the inferred viewing angle to the radio axis (Baker & Hunstead 1995).

In conclusion, ISO's MIR view, combined with radio imaging and NIR spectroscopy, has proven to be an efficient way of identifying a dusty quasar at $z = 1.5$. Recent ISOPHOT results on PG quasars have already revealed considerable dust emission between 25–200 $\mu$m (Haas et al. 2000). In ISO J1324−2016 ISOCAM provides evidence for the presence of hot dust (at 2.7 $\mu$m, rest frame) heated by an active nucleus. In this respect, ISO J1324−2016 appears to be a rare object. With the present data it is not possible to gauge the magnitude of a possible starburst contribution to the observed MIR luminosity. Higher resolution optical, infrared and radio imaging may enable a morphological study of ISO J1324−2016, which may in turn shed light on the origin of the active nucleus; so far, only 10% of the ERO population remain unresolved by HST (Stiavelli 2000). FIR/submillimeter observations would sharpen the SED picture, revealing the presence of cooler dust – responsible for the large peak predicted by the model in Fig. 4 – associated with star formation activity.

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