

The ISO-2MASS AGN survey: on the type-1 sources^{★,★★}

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Abstract. We combined the *ISOCAM Parallel Mode Survey* at $6.7\ \mu\text{m}$ (*LW2* filter) with the *Two Micron All Sky Survey* in order to obtain a powerful tool to search for AGN independent of dust extinction. Using moderate colour criteria $H - K > 0.5$ and $K - LW2 > 2.7$ we have selected a sample of 77 AGN candidates in an effective area of ~ 10 square degrees. By means of optical spectroscopy we find 24 ($\sim 30\%$) type-1 QSOs at redshifts $0.1 < z < 2.3$; nine of them have $z > 0.8$. About one third of the ISO-2MASS QSOs show so red optical colours, that they are missed in optical and UV AGN surveys like SDSS, 2DF, or HES. With a surface density of about $2\ \text{deg}^{-2}$ down to $R < 18$ mag the ISO-2MASS QSOs outnumber the $1.35\ \text{deg}^{-2}$ of the SDSS quasar survey by 50%; we find a combined optical-IR QSO surface density of $2.7\ \text{deg}^{-2}$. Since only two of the ISO-2MASS QSOs have also $J - K > 2$, the inclusion of the ISO mid-infrared photometry significantly extends the capabilities of the pure 2MASS red AGN survey. We suggest that the newly found red AGN resemble young members of the quasar population, and that quasars spend much of their lifetime in a dust enshrouded phase.

Key words. galaxies: fundamental parameters – galaxies: photometry – quasars: general – infrared: galaxies

1. Introduction

Attempts to overcome the limits by dust extinction in optical AGN surveys and to identify the entire AGN population – including type-2 and buried AGN – encompass surveys in the radio, X-ray and infrared (IR) ranges. However, only about 30% of AGN are radio-loud (Urry & Padovani 1995). Hard X-rays enabled the discoveries of elusive AGN completely hidden in starburst nuclei (Maiolino et al. 2003). However, there exists also a significant fraction of X-ray faint AGN (Wilkes et al. 2002), suggesting that also other search techniques should be considered. The finding of obscured AGN is further complicated by the contribution of the host galaxies, which may dominate the observed properties. Using IRAS $25\ \mu\text{m}/60\ \mu\text{m}$ colours far-IR searches already indicated that the local space density of

AGN may be significantly higher than deduced from optical searches (Low et al. 1988). Among far-IR dominant ULIRGs only few show AGN-typical mid-IR spectral lines (e.g. Armus et al. 2004) or X-ray evidence for powerful buried quasars (Ptak et al. 2003). Searching among the 2MASS survey for very red AGN the extreme $J - K > 2$ color selection reveals new type-1 AGN at redshifts $z < 0.8$ with moderate luminosities (Cutri et al. 2002). The FIRST-2MASS study finds about 20% previously overlooked radio-loud quasars not suspicious in the UV (Glikman et al. 2004). Although the contribution of the 2MASS red AGN to the cosmic X-ray background may be as high as 30% (Wilkes et al. 2003), a considerable fraction of the AGN population might still be missed.

The disadvantage of heavy extinction in optical surveys can turn into a valuable detection tool, when observing dust-surrounded AGN at near-infrared (NIR) and mid-infrared (MIR) wavelengths. There, the reemission of the dust heated by the strong radiation field of the AGN should be seen as IR excess. We have started a new approach, searching for AGN by means of their near- and mid-IR emission properties of the putative nuclear dust torus. The *ISOCAM Parallel Mode Survey* “ISOCP” (Cesarsky et al. 1996; Siebenmorgen et al. 1996; Ott et al. 2003; Ott et al. 2005) provides $6.7\ \mu\text{m}$ data for a large number of extragalactic sources and is therefore an ideal

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** Table 2 is only available in electronic form at <http://www.edpsciences.org>

hunting ground for a hitherto unknown population of AGN. The sample selection and first results from a subsample are described in detail by Haas et al. (2004). Also other MIR searches have been started using the Spitzer Space Telescope (e.g. Lacy et al. 2004). Here we report on the results for type-1 AGN from the full sample of those ISOCP sources which have 2MASS counterparts.

2. Data

From a sample of 3000 high galactic latitude ($|b| > 20^\circ$) sources detected on randomly distributed frames covering a total effective area of $\sim 10 \text{ deg}^2$ we have found unresolved ($FWHM \sim 6''$) objects with steep $2.2\text{--}6.7 \mu\text{m}$ slopes, which we consider as AGN candidates. By means of correlations with the 2MASS archive and by comparison with colour-colour and colour-magnitude properties of known sources we have excluded – as far as possible – contaminations like stars or pure star forming galaxies (Haas et al. 2004).

The selection criterion for the ISO-2MASS AGN is a good detection in the ISO *LW2* filter down to $F_{6.7 \mu\text{m}} \sim 1 \text{ mJy}$ as well as in all 2MASS filters, J , H , and K_s , respectively. In addition to these flux limits we apply, guided by the comparison with PG quasars and 3CR radio galaxies, only the moderate colour criteria $H - K_s > 0.5$ and $K_s - LW2 > 2.7$ (Vega-based system). By this procedure 77 candidates were selected, of which eight had redshifts available in the NED. For the remaining 69 sources we have performed optical spectroscopy at various telescopes.

3. Results and discussion

3.1. Properties of the ISO-2MASS AGN

Within our sample we find 24 broad-line type-1 AGN ($\sim 31\%$, redshift range $z = 0.1\text{--}2.3$), nine narrow-line type-2 AGN ($\sim 12\%$, $z = 0.1\text{--}0.3$), and 44 emission line galaxies with LINER and HII type spectra ($\sim 57\%$, $z = 0.03\text{--}0.3$). None of the objects turned out to be a star. The emission line galaxies, henceforth denoted type-3 sources, are heavily reddened ($H_\alpha/H_\beta > 10$) and their spectra show clear signatures of the host galaxy. Their high MIR/NIR, but low FIR/MIR flux ratio typical for AGN argues against pure starbursts. Essentially none of the sources has been detected by IRAS. The distribution of the different types of sources in the colour-colour diagram is shown in Fig. 1. While in $H - K_s$ only minor trends are present, we see a striking dependence in $K_s - LW2$: the type-1 and type-3 sources concentrate toward the right- and left-hand sides, respectively, while type-2 sources are more intermediate. This suggests that we see the hot dust emission best in the type-1 sources, while it is more obscured or intrinsically less prominent in some of the type-2 sources and in most of the type-3 ones. The type-2 and type-3 sources will be investigated in detail in a forthcoming paper. In the following discussion we consider only the type-1 sources and Table 1 summarises their parameters.

The K_s brightness of the type-1 AGN spans the range $12.4 < K_s < 15.5$. Figure 2 shows the distribution of K_s

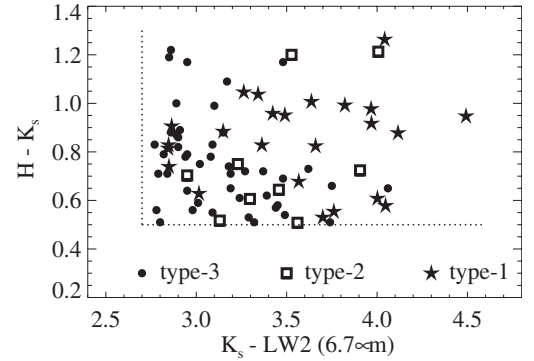


Fig. 1. IR colour-colour diagram of the ISO-2MASS AGN.

Table 1. Parameters of the ISO-2MASS type-1 QSOs.

2MASS	$F_{6.7 \mu\text{m}}$ [mJy]	Redshift	Remarks
z and type from this work			
J01363451+4112497	1.21	0.198	
J03005029-7938450	3.53	0.901	
J03080561-6535520	1.79	0.127	
J11323474-1952448	1.65	0.389	
J11353051-1425344	1.94	0.536	$J - K_s > 2$
J13250782+0541052	1.65	0.206	SDSS phot+spec
J13474549-0841059	1.43	0.754	
J14265292+3323231	2.59	1.083	
J16413748+6541140	1.60	1.082	
J17075650+5630136	1.75	1.019	
J17175947+4956261	2.07	1.018	
J20145083-2710429	2.44	1.444	
J22484115-5109532	16.90	0.101	
J23271158+0114469	3.46	0.468	SDSS phot
J23324586-1414242	2.51	0.315	
J23410667-0914327	8.49	0.236	SDSS phot
z and type from NED			
J00300421-2842259	31.35	0.278	RQ, $J - K_s > 2$
J01020053-3018259	2.24	1.033	RL
J12345816+1308549	2.12	2.364	SDSS phot
J12373357+1319063	1.33	0.150	SDSS phot
J14590760+7140199	3.11	0.905	RL (3C 309.1)
J15520240+2014016	5.09	0.250	
J16425879+3948369	13.82	0.593	RL (3C 345)
SDSS phot+spec			
J21145258+0607423	25.04	0.466	RQ

over z . Using a Λ cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{matter}} = 0.27$ and $\Omega_{\Lambda} = 0.73$, the type-1 sources exhibit an absolute K_s -band magnitude in the range of -25 to -30 , similar to the SDSS quasars. This qualifies them as QSOs, henceforth denoted ISO-2MASS QSOs. In this calculation no k -correction was applied; if done, it would further increase the luminosity of the objects. Five of the ISO-2MASS QSOs are detected by NVSS or FIRST, three being radio-loud with $F_{1.4 \text{ GHz}} > F_{2.2 \mu\text{m}}$.

Optical B - and R -band photometry of the sources is provided by the USNO catalogue (USNO-B, Monet et al. 2003), with a range of $15.7 < B < 19.7$ and $15.5 < R < 17.9$. We found that the B and R -band photometry is consistent with that

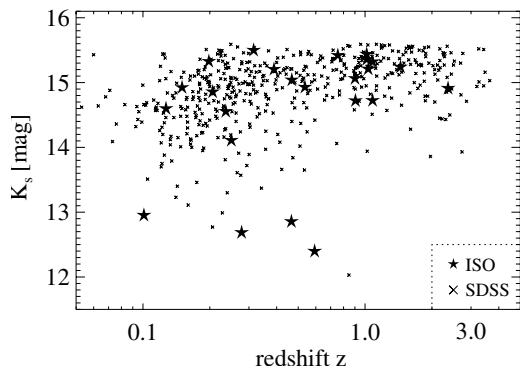


Fig. 2. Distribution of K_s magnitude and redshift for the ISO-2MASS type-1 AGNs and SDSS-QSOs (only every tenth object plotted).

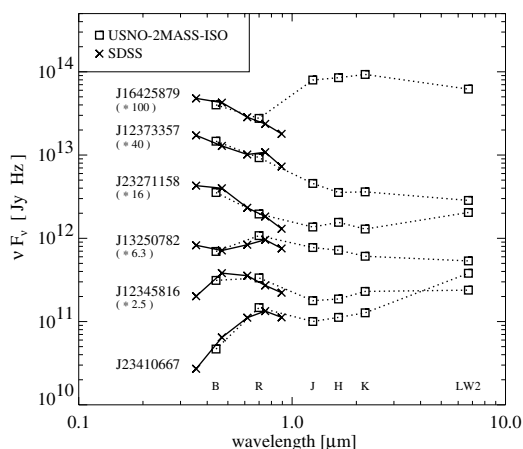


Fig. 3. SEDs of those six ISO-2MASS QSOs with SDSS photometry. Dotted lines refer to USNO-B photometry and solid lines to SDSS photometry. The good match confirms the USNO data.

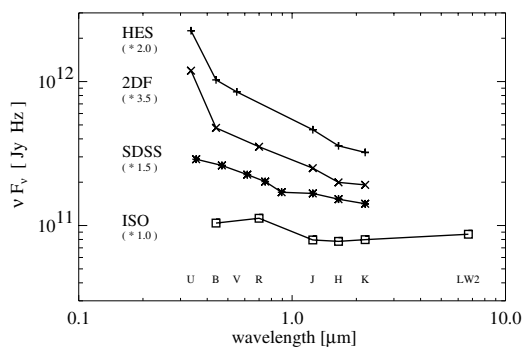


Fig. 4. Mean SEDs of QSO samples with 2MASS counterparts.

derived from the spectra. The ISO-2MASS AGN span a colour range $-0.4 < B - R < 2.2$; 42% (10/24) have $B - R > 1$. Figure 3 shows the MIR to optical spectral energy distributions (SEDs) for those sources for which also SDSS photometry is available. Even the mean SED shows red colours compared to other samples, especially at shorter wavelengths (Fig. 4).

3.2. Comparison with optical-UV selected QSOs

If the ISO-2MASS QSOs comprise the same QSO population as that found by optical-UV selected QSO samples, then the

number counts as well as the mean SEDs should be similar for suitably matched bins. We compare the ISO-2MASS QSOs with the quasars in the SDSS DR3 (Schneider et al. 2005), the 2QZ+6QZ catalogues of the 2DF survey (Croom et al. 2004), and the Hamburg/ESO quasar survey (HES, Wisotzki et al. 2000). We also correlated these reference catalogues with the 2MASS archive, thereby creating sub-samples hereafter called SDSS-2MASS, 2DF-2MASS, and HES-2MASS, respectively. Figure 2 shows the redshift and K_s -band magnitude distributions of the ISO-2MASS QSOs and the SDSS-2MASS QSOs. Apart from the low number statistics of the ISO-2MASS QSOs, we find that the redshift and K_s -band magnitude distributions of the ISO-2MASS QSOs and all three optical samples do not differ severely, so that a comparison of the number counts makes sense. However, the SDSS spectroscopy is limited to sources with $i > 15$ (Richards et al. 2002) which translates to $K_s > 13$ (only $\sim 10\%$ of the SDSS-2MASS QSOs have $i - K_s < 2$). Therefore we exclude all objects with $K_s < 13$ in the following discussion.

In order to compare the number of quasars found per deg^2 for the different samples we chose various bins down to the flux limits of the ISO-2MASS QSOs at $R < 18$ and $K_s < 15.5$ and separate also at $z = 0.8$. The USNO photometry yields on average smaller $B - R$ values compared with newer photometric samples, mainly because of differences in the B -band, while the R -band values are more comparable. In order to allow for a more homogeneous photometric comparison, we also used the R -band photometry from USNO for selecting the optical QSO sub-samples (Table 2). The basic results are illustrated in Fig. 5. The striking result is that for all reasonable bins the surface density of ISO-2MASS QSOs is by a factor of 1.5 to 10 higher than for the optically selected QSOs. We did not find any reasonable bins to match the surface densities of the IR- and the optically selected QSOs samples.

This result is remarkable as Vanden Berk et al. (2005) report a completeness of 80% to 95% for the SDSS quasar survey. We searched the SDSS DR3 for photometric and spectroscopic data of the 24 ISO-2MASS QSOs. Six have $ugriz$ photometry available; compared to the mean SEDs (Fig. 4) they show a more or less red SED, even shortward of the B -band (Fig. 3). According to the SDSS colour criteria (Richards et al. 2002) two of these six sources lie in the stellar loci and are not foreseen for SDSS spectroscopy, two seem to be potential QSO candidates and two have been identified spectroscopically as QSO. The extrapolation from these six sources indicates that the completion of the SDSS spectroscopy may at most double the optical colour selected number of QSOs, and that one third of the 24 ISO-2MASS QSOs will be missed by the SDSS spectroscopic QSO search due to star-like colours.

Figure 4 illustrates that shortward of the R -band the mean SED of the ISO-2MASS QSOs is significantly redder than that of the optically selected QSOs (with 2MASS counterparts), in particular for the 2DF-2MASS and the HES-2MASS QSOs, which show a strong upturn shortward of the B -band. Both results, the higher QSO surface density and the redder SEDs, are independent of the magnitude or NIR colour bins chosen. We conclude that the ISO-2MASS AGN survey discovers a QSO

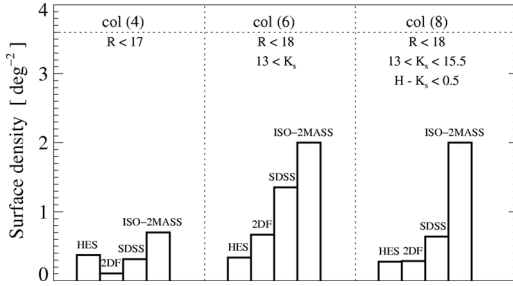


Fig. 5. QSO number counts of the ISO-2MASS and three optical surveys at three different bins. The column enumeration refers to Table 2.

population, about a third of which is clearly different from that found in the optical surveys.

On the other hand, down to $R < 18$ the 2DF and SDSS QSO surveys find about 40–50% blue QSOs which have $K_s > 15.5$, hence are fainter than the detection limit of the ISO-2MASS survey; these optical QSOs without 2MASS counterpart have on average bluer optical colours than those with 2MASS counterparts¹. To get an estimate of the entire IR- and optical QSO number counts down to $R < 18$ we add the surface density of ISO-2MASS and SDSS QSOs and subtract the intersection of both samples, i.e. those SDSS quasars that also fulfill our IR selection criteria ($R < 18$, $13 < K_s < 15.5$ and $H - K_s > 0.5$). Referring to Cols. 6 and 8 of Table 2 this corresponds to $\frac{20}{10} + \frac{5669}{4188} - \frac{2685}{4188} \approx 2.7 \text{ deg}^{-2}$ ($\sim 1.5 \text{ deg}^{-2}$ for $z > 0.8$, respectively), i.e. about a factor 2 higher than inferred from the SDSS QSO survey alone.

The fact that IR counts essentially add to the quasar surface density can most likely be ascribed to quasars (extended as well as pointlike objects) that have stellar colours. Remarkably, in the completeness test of the SDSS QSO survey by Vanden Berk et al. (2005) this population of quasars has largely been excluded. However our data show that these quasars with optical stellar-like colours comprise a considerable fraction of the total population of quasars and that they can most efficiently be discovered by IR colours.

3.3. Comparison with the 2MASS red AGN survey

Using the colour selection $J - K_s > 2$ the 2MASS red AGN survey found an extrapolated surface density of ~ 0.57 type-1 and type-2 AGN per deg^2 (Cutri et al. 2002), which become lower based on newer larger data sets (Cutri, priv. commun.). Two type-1 and two type-2 ISO-2MASS AGN match the criterion $J - K_s > 2$, resulting in $4/10 = 0.40$ AGN per deg^2 , roughly comparable to the 2MASS red AGN estimates. Thus the 2MASS red AGN are a proper subset of the ISO-2MASS AGN survey, as expected.

Due to k-correction effects the 2MASS red AGN survey is biased against sources with redshifts $z > 0.8$, hence against high luminosity sources (Cutri et al. 2002). Using a moderate colour criterion $H - K_s > 0.5$ (roughly corresponding to

$J - K_s > 1.2$ as used by Francis et al. 2004) the ISO-2MASS AGN survey in fact finds nine (out of 24) QSOs with $z > 0.8$. As a consequence the ISO-2MASS-QSOs reach by one to three magnitudes higher K_s band luminosities.

4. The nature of the ISO-2MASS type-1 QSOs

Combining the ISO 6.7 μm and 2MASS surveys we applied a moderate near- and mid-IR colour criterion to search for AGN. About 30% of the selected sources turned out to be type-1 QSOs. Part of them have colour properties similar to optically selected QSOs, but about 30% of them have red optical SEDs similar to stars, so that they might escape QSO identification in current optical colour surveys.

In the frame work of a quasar’s evolution from an initially dust-enshrouded object to a clean one (Sanders et al. 1988; Haas et al. 2003) we suggest that the red objects comprise young members of the QSOs population. If true, then the high (about 30%) fraction of these young objects indicates that the QSOs spend much of their life time in a dust surrounded phase, before they change their appearance becoming optically blue. Future studies may provide further clues to this issue as well as their contribution to the X-ray background.

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¹ Notably, the ISOCAM Parallel Survey reveals numerous (>100) $R > 18$ sources without 2MASS counterpart, which are not considered here. Their NIR and optical investigation is still ongoing.

Online Material

Table 2. Number counts of the IR and optical QSO samples for various bins. We adopt Poisson errors (\sqrt{N}) for the ISO-2MASS QSO sample. In the upper four blocks of the table we use the R -band photometry from the USNO catalog, in the lower two ones the R -band photometry is from 2DF and SDSS themselves (for SDSS: $R = g' - 1.14(g' - r') - 0.14$ according to Smith et al. 2002).

(1) Sample	(2) area	(3) total	(4) number (N) and surface density N/area (deg^{-2}) of quasars with									
			$R < 17$		$R < 18$		$R < 18$ $K_s > 13$		$R < 18$ $13 < K_s < 15.5$		$R < 18$ $13 < K_s < 15.5$ $H - K_s > 0.5$	
	deg^2	N	N	deg^{-2}	N	deg^{-2}	N	deg^{-2}	N	deg^{-2}	N	deg^{-2}
<i>R</i> -band photometry from USNO												
ISO-2MASS												
$z > 0.0$	~ 10	24	7	0.7	24	2.4	20	2.0	20	2.0	20	2.0
$z > 0.8$	~ 10	9	1	0.1	9	0.9	9	0.9	9	0.9	9	0.9
HES												
$B < 17$	> 1000	415	371	< 0.37	415	< 0.42	337	< 0.34	336	< 0.34	277	< 0.28
$B < 17$ and $z > 0.8$	> 1000	140	122	< 0.12	140	< 0.14	137	< 0.14	137	< 0.14	84	< 0.08
SDSS DR3												
$z > 0.0$	4188	44 298	1309	0.31	5713	1.36	5669	1.35	3149	0.75	2685	0.64
$z > 0.8$	4188	35 459	497	0.12	3303	0.79	3303	0.79	1213	0.29	846	0.20
2DF 2QZ+6QZ												
$z > 0.0$	721.6	19 304	76	0.11	484	0.67	483	0.67	253	0.35	205	0.28
$z > 0.8$	721.6	16 055	41	0.06	320	0.44	320	0.44	143	0.20	92	0.13
<i>R</i> -band photometry from SDSS and 2DF, respectively												
SDSS DR3												
$z > 0.0$	4188	46 420	568	0.14	4700	1.13	4657	1.11	2653	0.63	2212	0.53
$z > 0.8$	4188	37 322	300	0.07	3068	0.73	3068	0.73	1285	0.31	901	0.22
2DF 2QZ+6QZ												
$z > 0.0$	721.6	23 660	62	0.09	727	1.01	726	1.01	327	0.45	271	0.38
$z > 0.8$	721.6	19 775	32	0.04	486	0.67	486	0.67	161	0.22	115	0.46