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THE *AKARI* FIS CATALOGUE OF YSOS AND EXTRAGALACTIC OBJECTS

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ABSTRACT

The point sources in the Bright Source Catalogue of the *AKARI* Far-Infrared Surveyor (FIS) were classified based on their FIR and mid-IR fluxes and colours into young stellar object (YSO) and extragalactic source types using a Quadratic Discriminant Analysis method (QDA) and Support Vector Machines (SVM). The reliability of the selection of YSO candidates is high, and the number of known YSO candidates were increased significantly, that we demonstrate in the case of the nearby open cluster IC348. Our results show that we can separate galactic and extragalactic *AKARI* point sources in the multidimensioal space of FIR fluxes and colours with high reliability, however, differentiating among the extragalactic sub-types needs further information.

Key words: infrared: galaxies; open clusters and associations: individual: IC348; stars: formation

1. INTRODUCTION

The *AKARI* FIS Bright Source Catalogue (BSC, Yamamura et al. (2010)) as an all-sky catalogue opens the possibility to increase the number of known infrared bright YSOs and extragalactic objects. There were already successful attempts to separate point source types, eg. stars and galaxies by Pollo et al. (2010), and AGNs by Ichikawa et al. (2012). Wang et al. (2014) classified *AKARI* point sources into various extragalactic types using multi wavelength photometry and spectral energy distribution (SED) templates. In our previous paper (Tóth et al., 2014) statistical methods were applied to *AKARI* and *WISE* photometric data to separate stellar, YSO and extragalactic types of AKARI point sources. We showed that the AKARI YSOs are often associated with Planck cold clumps (Planck Collaboration, 2011b), and have an overdensity towards galactic shells (Tóth et al., 2014). While testing the overall distribution of galactic star formation with the AKARI YSO catalogue we also hope to locate and describe YSO clusters (see eg. Tóth et al. (2013)). In this paper we recalculate the reliability of our YSO classification and demonstrate the use of our catalogue of *AKARI* YSO candidates. We also report the results of our attempt to identify AKARI extragalactic point source types.

2. ANALYSIS OF THE *AKARI* FIS POINT SOURCES

The *AKARI* FIS BSC lists 427071 point sources. In our study we used sources with the highest quality flag "3" in the two wide-filter bands ("WIDE-S" and "WIDE-L", with band centres of 90 μm and 140 μm" respectively). That means confirmed sources with reliable flux densities ($\approx$ 20% uncertainty). We combined *AKARI* and *WISE* (Cutri et al., 2012) all-sky photometric data (see Tóth et al. (2014) for further details).

2.1. Object types, colours and selection

The first step of the classification was an investigation of point sources with already known types. We used a search radius of 30$''$ to find associated entries in the SIMBAD database. The mid-IR and FIR colour distribution

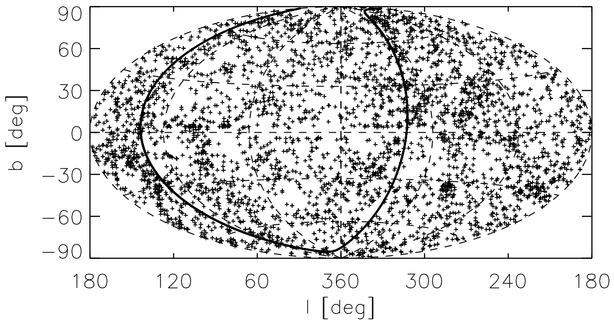

Figure 1. Celestial distribution of extragalactic objects classified with QDA in galactic coordinate system, using Aitoff-projection. The super galactic equator is shown with the thick solid black line.

of extragalactic objects, YSOs and reddened stars are similar, thus those are located in highly overlapping regions on the colour–colour and brightness–colour planes. For example, the average [F90/F140] colour of the SIMBAD "Y*O" (YSO), "G" (galaxy) and "pA*" (post-AGB star) types are -0.511 ± 0.238, -0.513 ± 0.24 and -0.536 ± 0.231, respectively. Separating amoprhous regions in the multi-dimensional parameter space can not be made by cutting it with a few planes. We can handle that with advanced statistical methods, like Quadratic Discriminant Analysis. The classification was based on a 6D parameter space that contained the *AKARI* FIS BSC [F65/F90], [F90/F140], [F140/F160] colours and the [F140] flux along with the WISE W1-W2 colour and the W1 magnitude.

2.2. *Quality check of the selection*

As described in Tóth et al. (2014), the *AKARI* FIS BSC sources were classified into 3 main object types, namely candidate YSOs, evolved stars and galaxies. The goodness of our automatic classification was measured comparing the total number of candidates of a given type listed also in SIMBAD to the number of those which had the correct SIMBAD object types. For our YSO candidates the approving SIMBAD types were "Y*O" (YSO), "TT*" (TTauri), "pr*" (pre-main sequence star), "Or*" (variable star of Orion type) and "FU*"(variable star of FU Ori type). The fraction of contaminating sources was then estimated using the number of SIMBAD associations with any other SIMBAD object type.

A refreshed list of the SIMBAD associations was created and compared to Tóth et al. (2014), and the estimation of the goodness and contamination was recalculated. In the case of the YSO candidates we were able to keep 84.7% of the YSO-like sources.

We found 18494 sources that had colours and brightness values similar to extragalactic objects, but a large number of SIMBAD stars were identified among them. Therefore we created a training sample tailored for identification of extragalctic sources by using SIMBAD approved galaxies located outside the Galactic mid-plane ($|b| > 3°$). This way, 5138 extragalctic source candidates were identified using the QDA method. 4451 (86.6%) of them are known extragalactic objects based on their SIMBAD identification. 297 more sources were identified as "IR" infrared source or "Rad" radio source. 262 sources were identified as some kind of Galactic object type and 128 remained unidentified.

The all-sky distribution of our *AKARI* extragalactic candidate point sources has an overdensity along the supergalactic plane as shown in Figure 1. It may indicate that a considerable number of these objects are members of the Local Supercluster. There are also other local density enhancements seen, an interpretation of those needs further investigation.

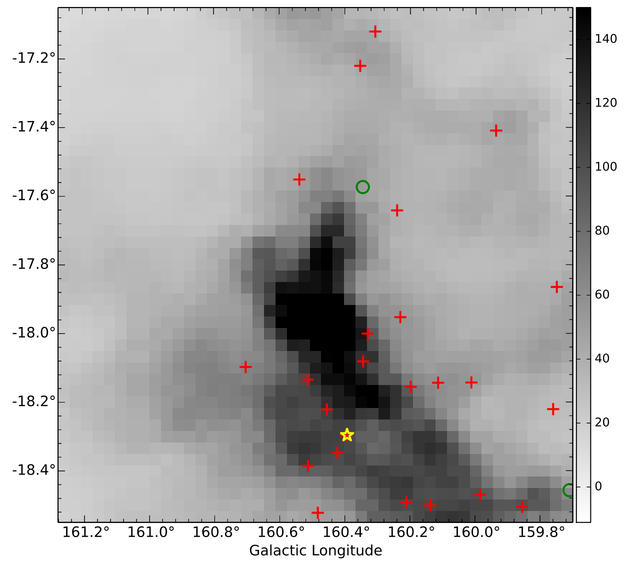

Figure 2. New candidate YSOs in IC348. Class I (red plus) and Class II (green circle) YSOs are overlaid on the Planck 857 GHz image. The 857GHz (350μm) intensity varies from 10MJysr^{-1} to over 140MJysr^{-1} in the image (Planck Collaboration, 2011) showing IC348 and the G159.6-18.5 HII region. The yellow star marks the position of the Class I source AKARI-FIS-V1 J0342443+315028. See also its SED in Figure 3).

3. USE OF THE *AKARI* CATALOGUES

3.1. *New YSOs in IC348*

IC348 is a 2-3 Myr old cluster, located at the edge of the Perseus molecular cloud. It contains 283 spectro-

Table 1
New candidate YSOs towards the IC348 open cluster. The columns are: *AKARI* name; galactic coordinates L and B; and YSO class (Lada, 1987).

AKARI name	L [deg]	B [deg]	Lada class
0339531+320754	159.710	-18.457	Class II
0341483+323334	159.751	-17.865	Class I
0340454+321703	159.761	-18.221	Class I
0340146+315958	159.855	-18.506	Class I
0343508+324756	159.938	-17.410	Class I
0340484+315703	159.985	-18.471	Class I
0341526+321102	160.012	-18.144	Class I
0342119+320746	160.114	-18.145	Class I
0341140+314950	160.138	-18.502	Class I
0342291+320359	160.198	-18.157	Class I
0341327+314811	160.211	-18.493	Class I
0343123+321211	160.230	-17.954	Class I
0344111+322613	160.240	-17.643	Class I
0346006+324743	160.307	-17.122	Class I
0343259+320626	160.330	-18.002	Class I
0343125+320209	160.344	-18.083	Class I
0344465+322554	160.345	-17.575	Class II
0345514+324116	160.353	-17.222	Class I
0342443+315028	160.396	-18.299	Class I
0342402+314714	160.423	-18.349	Class I
0343095+315136	160.455	-18.223	Class I
0342216+313650	160.483	-18.524	Class I
0342531+314200	160.513	-18.387	Class I
0343395+315339	160.514	-18.136	Class I
0345292+321931	160.539	-17.553	Class I
0344254+314817	160.704	-18.099	Class I

scopically confirmed members in a relatively compact ($20'' \times 20''$) region (Lee et al., 2011). It is located at a distance of 320 pc, based on Herbig (1998). The cloud G159.6-18.5 was recognised as an HII region and a dusty shell of enchanced FIR emission with a diameter of 1.5 degrees by Anderson et al. (2000) and Watson et al. (2005).

We found 26 new YSO candidates in the IC348 cluster. The distribution of these *AKARI* FIS YSOs is shown in, Figure 2. As part of our survey of the Taurus-Auriga-Perseus region (Tóth et al., 2015) young stellar objects were classified into different evolutionary classes, based on their spectral index, α or bolometric temperature, T_{bol}. The α index is the slope of the near- and mid-infrared part of the spectral energy distribution (see Lada (1987), Greene et al. (1994) and Andre et al. (1993)), while T_{bol} is defined as the temperature of a blackbody, whose spectrum has the same mean frequency as the observed spectrum (Myers and Ladd, 1993). Class 0 objects are undetectable at $\lambda < 20\mu$m, their bolometric temperature is below 70 K. The spectral index ranges for Class I; Flat spectrum; Class II; and Class III YSO types are: $\alpha > 0.3$; $0.3 > \alpha > -0.3$; $-0.3 > \alpha > -1.6$; and $-1.6 > \alpha$ respectively. The bolometric temperature ranges for Class I; Class II; and Class III source types are: 70K$< T_{bol} <$ 650K; 650K$< T_{bol} <$ 2800K; and $T_{bol} >$ 2800K respectively.

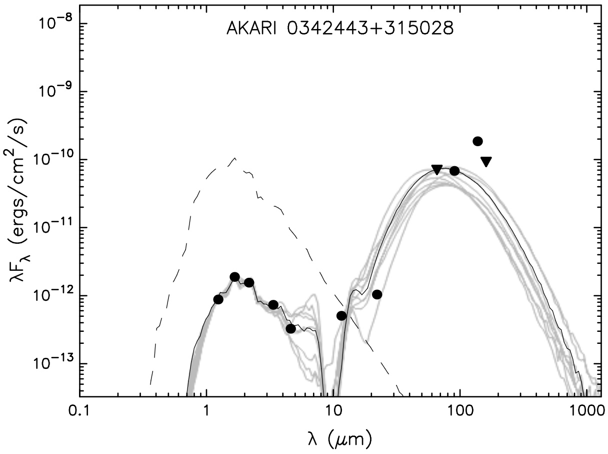

Figure 3. SED of AKARI-FIS-V1 J0342443+315028, a YSO in IC348, fitted with the YSO models of Robitaille et al. (2007). Filled circles show the fitted 2MASS, *WISE* and *AKARI* fluxes, triangles indicate upper limits. The solid black line shows the best-fitting model, and the grey lines show the 9 next best models. The dashed line shows the stellar photosphere of the best-fitting model.

There are 24 Class I and 2 Class II sources among the newly discovered YSOs of IC348, as listed in Table 1. The YSOs are mostly concentrated at the dusty ISM that is seen as a bright extended region in the Planck 857 GHz image (Figure 2). The Lada classes are marked with red pluses (Class I) and green circles (Class II).

The stellar parameters (e.g. stellar mass, age, temperature; disk and envelope mass and size) of the candidate YSOs were estimated using online available precomputed YSO SEDs[1]. Robitaille et al. (2007) presented a grid of 20000 radiation transfer models of YSOs in different evolutionary stages and from ten different viewing angles, resulting in 200000 SEDs. The best fitting Robitaile models provided us the parameter values of AKARI YSO candidates. To estimate the error of the fit the 9 next best fitting models were used, the minima and maxima of each of the parameters were derived from those. Our succesful SED fits also support the validity of our statistical YSO selection.

A sample of the fitted SEDs is shown in Figure 3

[1]http://caravan.astro.wisc.edu/protostars/

Table 2

Wang et al. (2014) object types and the reliability of classification into each types using various classification algorithms. The reliability is measured as the ratio of sources which were reclassified into their own group by our selection method. SVM types from 1-9 correspond to the eps-regression type with radial, linear and polynomial kernel, the C-Classification method with radial, linear and polynomial kernel and to the nu-regression method with radial, linear and polynomial kernel, again.

Object type	known	LDA	QDA	SVM1	SVM2	SVM3	SVM4	SVM5	SVM6	SVM7	SVM8	SVM9
no template contributes > 50%	5	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0
cirrus dominated	2039	96.1	88.3	91	93.7	98.6	97.4	97.7	98.7	89.5	67.4	66.4
M82 dominated	203	3.4	20.2	41.9	43.4	19.7	2.0	0	4.9	45.8	76.8	73.9
A220 dominated	502	29.8	37.6	22.3	0.4	2.2	38.2	33.1	22.1	20.9	3.8	1.8
AGN dust torus dominated, at 60 μm	10	50.0	0.0	10.0	0.0	10.0	0.0	0.0	20.0	10.0	0.0	10.0
ysb dominated	101	32.7	34.7	9.9	0	3.9	23.8	0	24.8	8.9	0	6.9
cool cirrus dominated	111	3.6	33.3	0	0	0.9	0	0	0	0	0	0.9
Average		30.8	30.6	25.0	19.6	22.2	23.1	18.7	24.4	25.0	21.1	22.8

for AKARI-FIS-V1 J0342443+315028, a new YSO without any former SIMBAD association. We classified the source as a Class I / Flat object based on its $T_{bol} = 643$K and $\alpha = -0.1$ values. The parameters from the 10 best fits (with minimum, maximum values in parentheses) are the following: age is $t \approx 2.1 \times 10^5$yr ($5.8 \times 10^4yr< t < 2.3 \times 10^5$yr), stellar mass is $M \approx 0.30$M$_\odot$ (0.15M$_\odot < M < 0.35$M$_\odot$) , stellar radius is $r \approx 2.6$R$_\odot$ (2.4R$_\odot < R < 3.2$R$_\odot$) R$_\odot$, temperature is $T \approx 3350$K (2900K$< T < 3500$K) and disk mass is $M_{disk} \approx 1.6 \times 10^{-3}M_\odot$ ($5.6{\times}10^{-5}$M$_\odot < M_{disk} < 1.3 \times 10^{-2}$ M$_\odot$).

3.2. New extragalactic objects?

We searched counterparts of the 128 extragalactic candidates without SIMBAD identification in the Rowan-Robinson catalogue of galaxies (Wang et al., 2014) using a 60″ search radius, but did not find any. We note that only 2 of these sources have an associated *IRAS* point source. A crosscorrelation with the NASA/IPAC Extragalactic Database (NED) shows, that 30% of our 128 SIMBAD unidentified point sources are galaxies, few of them are part of a galaxy, but most of them are either not listed in NED, or with an object type of radio or infrared source. We considered these as new extragalactic object candidates (NEOCs). Checking the optical and infrared appearance of the NEOCs individually is underway, detailed results will be published elsewhere.

3.3. Classification into extragalactic subtypes

We cross-correlated our QDA galaxy candidates with the Rowan-Robinson catalogue (Wang et al., 2014), and created a training sample based on their classifications. They listed 7 sub-types for their identified objects: (1) cirrus dominated, (2) M82 dominated, (3) A220 dominated, (4) AGN dust torus dominated, at 60 μm, (5) ysb dominated, (6) cool cirrus dominated, (7) detected at 60 μm only and used subtype (0) for point sources where no template contributes over 50%.

In order to achieve the best possible result we carried out various classifications with different statistical approaches. Linear and Quadratic Discriminant Analysis (LDA, QDA) are described in more detail in our previous paper (Tóth et al., 2014). Support Vector Machines (SVMs) are a class of supervised learning algorithms, created as an extension to nonlinear models of the generalized portrait algorithm developed by Vladimir Vapnik (Vapnik, 1995) for classification in a multidimensional parameter space. A detailed description can be found in Malek et al. (2013). Our results of the various methods are summarised in Table 2, that shows that we can separate cirrus dominated objects (type 1 of Wang et al. (2014)) from the other sub-types, but we cannot achieve the same level of confidence with the other sub-types with any of our statistical methods.

4. CONCLUSIONS

Our results show that we can distinguish YSO and extragalactic source candidates from the other types of objects with high reliability by applying a QDA method for object classification on *AKARI* FIS BSC and *WISE* data. We also conclude that differentiating among the extragalactic sub-types needs further information. Follow-ups may approve our classification of the NEOCs.

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