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INFRARED CHARACTERISTICS OF THE BIS CATALOG OBJECTS

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ABSTRACT

We studied several color-color infrared diagrams of the 276 late type stars of the BIS catalog. For 95 of these stars we derived spectral classification from our slit spectroscopy. From the 2MASS color diagram we concluded that none of the sample stars is a dwarf. The WISE 3.4-12 vs 12-22 plot is the best to discriminate the variability type (Mira, irregular and not-variable), as well as carbon stars. IRAS colors are less useful due to the poor quality of the data for most of the BIS stars. Mixed plots involving 2MASS, AKARI and WISE were also explored: the 2MASS-AKARI J-[S09] vs [S09]-[L18] plot is efficient to discriminate carbon and Mira stars. From the color plots and our spectroscopy we can statistically predict that in the whole BIS catalog no other dusty carbon star is present, while a few Miras and CH or R carbon stars could be discovered. Only about 15% of the BIS stars are of early M type.

RESUMEN

Estudiamos diagramas color-color en el infrarrojo de 276 estrellas tardías del catálogo BIS. Obtuvimos clasificaciones espectrales para 95 de ellas. Con el diagrama de color del 2MASS concluímos que ninguna de las estrellas estudiadas es enana. La gráfica 3.4-12 vs 12-22 del WISE permite diferenciar el tipo de variabilidad (Mira, irregular, no variable, o estrellas de carbón). Los colores del IRAS son menos útiles por la pobre calidad de los datos de muchas estrellas BIS. Se exploraron varias gráficas de datos del 2MASS, AKARI y WISE. La gráfica 2MASS-AKARI J-[S09] vs [S09]-[L18] es útil para diferenciar entre las estrellas de carbón y las Miras. Con las gráficas de colores y la espectroscopía que obtuvimos predecimos estadísticamente que en el catálogo BIS no existe otra estrella de carbón con polvo, pero puede haber algunas estrellas Miras y de carbón tipo CH o R aún no descubiertas. Alrededor del 15% de las estrellas BIS son de tipo M temprano.

Key Words: — stars: infrared sources — stars: late type — stars: variables: general

1. INTRODUCTION: BYURAKAN – IRAS STARS CATALOG

The first major mission covering mid- and far-infrared (IR) was the InfraRed Astronomical Satellite (IRAS) in 1983, which surveyed about 96% of the sky in four bands centred at 12, 25, 60, and 100μm. Two general catalogs were produced, the IRAS Point Source Catalog IRAS PSC (1988) and the IRAS Faint Source Catalog (FSC; Moshir et al. 1989), more useful for extragalactic studies.

Recent work by Abrahamian et al. (2015) made a cross-check of the PSC and FSC catalogs using a new cross-correlation technique and establishing a correspondence between these two catalogs and a cross-correlation with more recent IR missions: 2MASS (1.25, 1.65 and 2.17 μm, Cutri et al. 2003; Skrutskie et al. 2006), WISE (3.4, 4.6, 12 and 22 μm, Cutri et al. 2013), and AKARI (9 and 18 μm, IRC, Ishihara et al. 2010; FIS, Yamamura et al. 2010). In this way, accurate positions for IRAS sources and fluxes at 17 bands from J, H, K to far-IR were provided.

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Infrared data available from several archives, make it possible to build many colour-magnitude and colour-colour diagrams for the study of the distribution of objects and for a first characterisation of these sources, finding possible groupings, as well as unique objects. A number of such statistical studies have been published by several groups (e.g. Ita et al. 2009, 2010; Kato et al. 2012; Murata et al. 2014; Nikutta et al. 2014; Tu & Wang 2013; Tisserand et al. 2013). Accurate optical identifications of IR sources are important for further studies and for the comparison of the optical and IR characteristics of the objects. In the PSC Vizier catalog (II/125), 142,228 associations are given (often several associations for the same IRAS source), accomplished by cross-correlations with several optical catalogs. Similarly, in the FSC Vizier catalog (II/156A), 235,935 associations are given. However, they should be verified and may be used for preliminary studies only. A number of studies were devoted to optical identifications of IRAS sources using positions and fluxes, very often pre-selecting by types of objects and/or galactic latitudes. Among these projects, one was conducted by Mickaelian (1995) in the Byurakan Astrophysical Observatory using DSS images and low-dispersion spectra from the Markarian Survey in the area with $\delta > +61^o$ and galactic latitude b $> +15^o$. Identifications were accomplished for all 1578 IRAS PSC sources present in the area, without any discrimination in order to keep the completeness. Later on, stars and galaxies were denoted as Byurakan IR Stars (BIS) and Byurakan IR Galaxies (BIG). Several lists of IRAS stellar sources were published by Mickaelian and Gigoyan between 1997 and 2001; the resulting catalogs provided optical and IR data for 276 IRAS BIS objects (see Mickaelian & Gigoyan 2006).

In order to clarify the nature of the stars included in the BIS catalog we have started a systematic collection of all the information available in the literature and have acquired new data. In a companion paper (Gaudenzi et al. 2017, hereafter G17) we have studied the optical spectroscopic and variability characteristics of a subsample of 94 BIS targets. The present work is dedicated to the IR characteristics of the whole BIS catalog (275 stars, since BIS 028 is a planetary nebula). We will use all the available data from the following catalogs: 2MASS, WISE, AKARI, and IRAS. We will also use the information gained from our optically studied subsample to interpret the infrared color-color plots and make statistical predictions from the overall stellar content of the whole BIS sample.

2. OUR TARGETS

The BIS catalog contains candidates of several spectral types: M-type and carbon-type stars, Mira-type and semi-regular (SR) variables, OH and SiO sources, and unknown sources surrounded by thick circumstellar shells. Most of the sources are poorly studied both from the photometric and spectroscopic point of view, and only a few of them are classified as variables in the GCVS (Samus et al. 2017) or VSX (Watson et al. 2016) catalogs. As described in G17, we have revised the spectral types and the variability behavior, and have determined a number of physical parameters for 1/3 of the BIS studied sources. Here we briefly remember the results relevant for the discussion of the infrared color-color diagrams described below.

Variability class (1): Mira type variables *BIS 007; 116; 133 (IY* Dra*); 196; 267* . With the exception of BIS 116 these are late type Miras, varying by more than 1.1 mag depending on the phase.

Variability class (2): semi-regular, irregular variables *BIS 001; 002; 003; 004; 006; 014; 015; 032; 036; 037; 038; 039; 043 (KP* Cam*); 088; 103; 104; 106; 120; 122; 123; 126; 132; 136; 138; 142; 145; 154; 156; 167; 168; 170; 173; 184; 198; 200; 207; 209; 211; 212; 213; 214; 216; 219; 226; 264; 271; 276*. We have grouped here semiregular and irregular variables with visual amplitudes larger than 0.3 magnitudes. The spectral types are from M5 to later ones.

Variability class (2/3): small amplitude variability *BIS 010; 107; 113; 172; 174; 201; 224; 255; 275; 285*. These stars show small ($<$ 0.3 magnitudes), aperiodical variations; with the exception of BIS 113, (M7) the spectral types are in the range M3 - M5.

Variability class (3): very stable stars *BIS 034; 044; 067; 087; 099; 102; 110; 137; 143; 155; 194; 197; 199; 203; 210; 228; 247; 248; 256; 260*. The level of optical variation is never larger than 0.2 magnitudes; the spectral types are in the range M0 - M4.

Carbon stars: *BIS 036; 184 (HP* Cam*); 222; 194*: all are N giants. The first three stars are irregular variables, embedded in a dusty envelope; BIS 194 is stable.

3. COLOR-COLOR DIAGRAMS

There is a wide literature describing the use of homogeneous and non-homogeneous data sets combined in several ways with the aim of distinguishing different types of sources in color-color diagrams.

During our work on the infrared data we applied already tested combinations and investigated the possibility of finding new efficient discriminators for late type stars. In what follows we will describe some of the diagrams that we consider the most successful and will mention others, also useful for our purpose. We will discuss and compare our results with those already known for the most popular diagrams.

When non-homogeneous data are considered, variable stars are most probably observed in different photometric phases, but we have verified that this does not affect their position in the color-color diagrams (see § 3.4). This can be explained, because the variability amplitude decreases with increasing wavelength, and is seldom larger than 0.5 mag already at K waveband.

As stated above, the diagrams include the sources of the BIS catalog not studied in G17. They are plotted as open triangles in all figures; from the NSVS light curves (Wozniak et al. 2004a), 54 are strongly variable (Class 1 or 2 of our classification), 66 are very stable, 27 show minor oscillations (class 2/3), the remaining are not present in the NSVS database.

3.1. 2MASS *(1.25, 1.65, 2.17μm)*

In the near infrared the data for almost all our targets are available in the 2MASS catalog. To discriminate dwarf/giant luminosity class, we used the traditional color-color plot $J-H$ vs $H-K$ (Bessel & Brett 1988; Leggett et al. 2002; Reid & Cruz 2002; Kirkpatrick et al. 1999; Cruz et al. 2003). We have transformed the 2MASS magnitudes into the Bessel & Brett system using the formulae given in the Explanatory Supplement to the 2MASS Second Incremental Data Release[5] and in Carpenter (2001). The results presented in Figure 1 show that among the stars studied in G17 none is located in the dwarfs region, namely $(J-H) < 0.7$ mag and $(H-K) > 0.15$ mag, while the colors are all typical for giants and AGB stars (see Figure A3 and Tables II and III of Bessel & Brett 1988). The M stars occupy different regions depending on their spectral types: as expected, the stable stars are in the blue corner. Among the variable stars, all the Miras lie below the bulk populated by the irregular variables, in accordance with the well established results found by the SAAO astronomers in their extensive studies (e.g. Feast et al. 1990). In addition to this result, this plot confirms its usefulness to point out heavily obscured, long period variables. Actually, on the

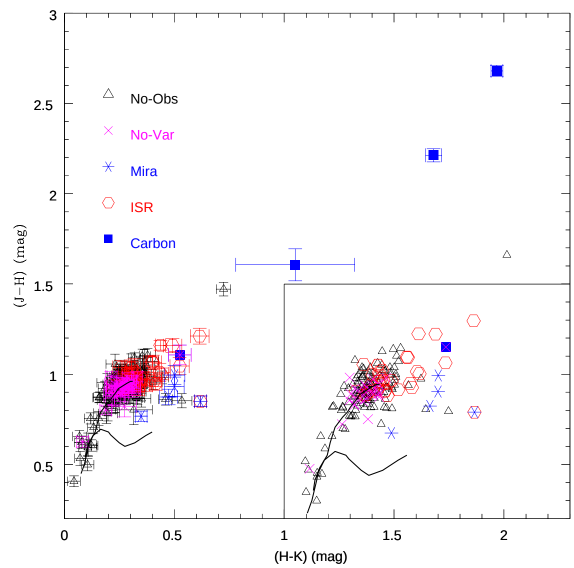

Fig. 1. $J-H$ vs $H-K$ color-color diagram of all the BIS sources with 2MASS magnitudes. The inset is a zoom of the region in the lower left corner. The symbols indicate our variability classes: magenta crosses= not variable; blue asterisk= M Mira; red polygon=irregular-semi-regular; filled blue squares= carbon stars; black open triangles= stars not yet spectroscopically observed. Error bars are not indicated in the inset. The two lines show the locus of the giants(upper) and dwarfs (lower) from Bessel & Brett (1988). The separation starts at about spectral type K9. The color figure can be viewed online.

basis of their spectra in G17 we classified BIS 036, 184 and 222 as N-type dust enshrouded stars. In the $J-H$ vs $H-K$ diagram these stars are well separated from the others, and located along the path defining heavily obscured, mass losing, long-period N-type AGB stars (van Loon et al. 1997). The colors of the fourth carbon star BIS 194 place this star among the semi-regular M variables, but they are also nicely aligned with the dusty carbon stars.

3.2. WISE *(3.4, 4.6, 12, 22 μm)*

The WISE magnitudes have a widespread application in searching for reliable criteria to define occupation regions of the various infrared sources in different types of diagrams. The huge amount of detected sources allows statistical approaches, but hampers satisfactory results to be obtained if the original data are not matched with catalogs of known objects and with theoretical models. Tu & Wang (2013) have investigated different color-color diagrams to efficiently separate C-rich from O-rich stars.

[5] `http://www.ipac.caltech.edu/2mass/releases/second/doc/~sec6_3.html`

According to these authors, even their best diagram ($W2-W3$ vs $W1-W2$) did not reach the goal. Lian et al. (2014), and Nikutta et al. (2014) have overlapped DUSTY models to observations in different color-color diagrams, among which the ones used by Tu & Wang (2013) and $W1-W2$ vs. $W3-W4$ which give more convincing results.

Almost all the stars of the BIS catalog are present in the WISE database. We have tested all the 15 combinations of the WISE colors, looking for a criterion able to distinguish not only the spectral types, but also the variability classes. We remember (from G17) that knowing spectral types and photometric behaviors, we obtained satisfactory results in this sense too.

In Figure 2 of Rossi et al. (2016) we showed two such diagrams: $W1-W2$ vs $W3-W4$ and $W1-W2$ vs $W1-W4$. The first diagram is efficient to separate dusty carbon from O-rich stars, and the Mira stars lie in a narrow region of the x axis, clearly isolated above the other variables. The non-obscured N stars and the CH stars cannot be isolated in this diagram. The second diagram is more confusing.

In the present paper we examine two not yet explored diagrams: the $(W1-W2)$ vs $(W2-W4)$ and $(W1-W3)$ vs $(W3-W4)$ (see Figure 2). In this figure we do not report individual error bars to avoid confusion in the lower part of the diagrams. The mean values are indicated by the two crosses at the corners. The large σ of $W1-W2$ and $W1-W3$ is due to the spread of the uncertainties of $W1$ which have a mean value of 0.18 mag.

In the upper plot the early type, non variable stars are tightly grouped in the lower left corner ($0.08 \leq W3-W4 \leq 0.23$ and $-0.2 \leq W2-W4 \leq 0.3$), the semi-regular variables are distributed along a diagonal strip in the lower part of the diagram, and all the confirmed M Miras lie above the strip; the carbon stars, including the naked, stable BIS 194, are aligned along a separate path in the upper region, far from all the other stars. The lower plot is less efficient in separating C-rich from O-rich stars. BIS 184 is not reported in these plots because of the large uncertainties of its WISE magnitudes.

3.3. *IRAS* (*12, 25, 60 μm*)

The IRAS database was used by Mickaelian & Gigoyan (2006), to select the original BIS sample. We remember that the data are released with fluxes in Jansky while in the diagrams the magnitudes are normally used. We have located our stars in the classical [25]−[60] vs [12]−[25] color-color plot, where the magnitudes are computed as $-2.5\log(\text{Flux})$ in order

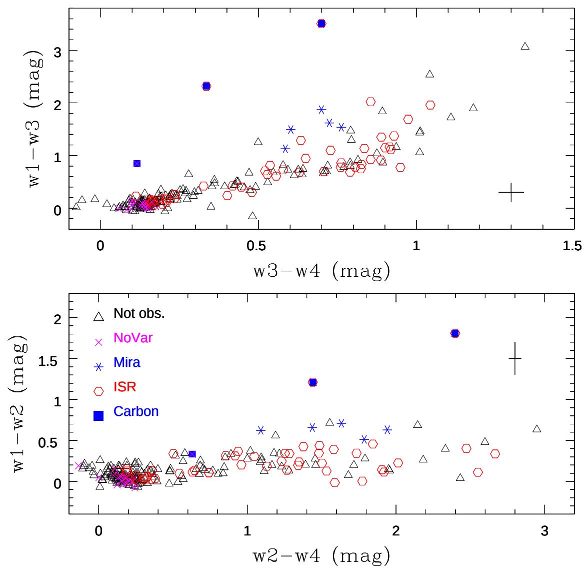

Fig. 2. WISE color-color diagram of the BIS stars: 3.4−12 $(W1-W3)$ vs $12-22$ $(W3-W4)$ and $3.4-4.6$ $(W1-W2)$ vs $4.6-22$ $(W2-W4)$. The mean values of the errors are indicated by the two crosses. $[\sigma(w1-w2) = 0.19, \sigma(w2-w4) = 0.091, \sigma(w1-w3) = 0.18, \sigma(w3-w4) = 0.04]$. The color figure can be viewed online.

to have a direct comparison with Figure 5b of van der Veen & Habing (1988). In Figure 3 the different symbols indicate the regions of the classification scheme by van der Veen & Habing (1988): Region II, variables with young O-rich shells; Region IIIa, variables with O-rich shells; Region VIa, non-variable stars with relatively cold dust at large distances; Region VIb, variables with hot dust nearby and more distant cool dust; Region VII , stars with evolved C-rich circumstellar shells. To avoid confusion we have included only stars of the BIS catalog having known spectral type and variability class from G17. The pattern does not change adding the remaining stars. The numbers indicate the variability class defined above (1 = Mira type, 2 = semi-regular/irregular variables, 3 = non variable stars). To evaluate the significance of the result we must remember that only quality factors, not absolute uncertainties are reported in the IRAS database. For our stars we remark that at 60μm only four stars have quality factor $q = 3$, seven $q = 2$ and 59 $q = 1$, implying that most of the positions might be affected by the low precision of the fluxes. We have discarded a few stars having quality factor 1 already at 25μm and being too far from the bulk of the diagram.

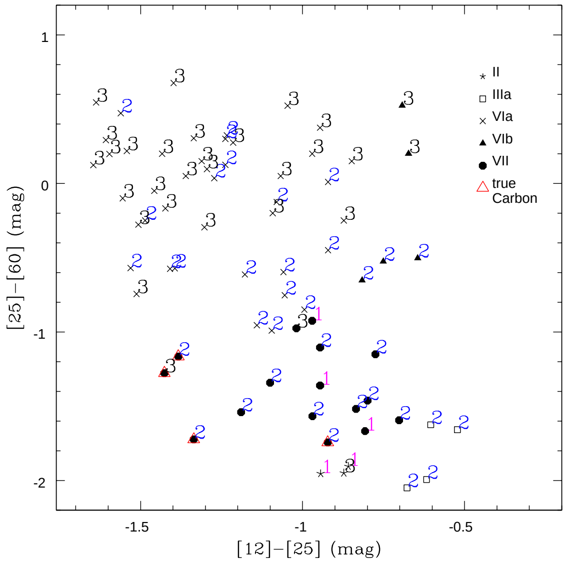

Fig. 3. IRAS [12]−[25] vs [25]−[60] color-color diagram of our target stars. The symbols correspond to the spectral classification by van der Veen & Habing (1988). Spectroscopically confirmed carbon stars are indicated by red triangles. The roman numbers indicate our variability class. The color figure can be viewed online.

The location of the stars presented in Figure 3 is statistically in agreement with the classification by van der Veen & Habing (1988) although this scheme appears not useful to give indication about the stellar variability of faint sources. Only few stable stars are not placed in Region VIa, where on the contrary, many strongly variables are located. Concerning the spectral types, the four carbon stars are all placed in the expected Region VII, occupied by M type variables too and by the stable BIS 113; they all have quality factors equal to 1. Computing the magnitudes according to the Explanatory Supplement to the Point Source Catalogue (IRAS PSC 1988) would only shift the axes but would not change the relative positions of the sources.

3.4. AKARI *(9 and 18 μm) and Composite Diagrams*

Before investigating composite diagrams we have checked the correlation between magnitudes of similar wave-bands in different catalogs. Our main purpose was to verify the efficiency of composite color-color diagrams. For this reason and taking into account the lower variability amplitude in the far IR, we considered all the stars of the BIS catalog, including those not present in G17. The results shown in Figure 4 indicate a general good agreement between AKARI, IRAS, and WISE, irrespective of the spectral types. The good correlation along the whole range of magnitudes between AKARI and IRAS is also due to the lack of data points in the AKARI catalog for faint stars. Many of these last stars are present in IRAS, though with low quality factors, resulting in a worse correlation with WISE, which has a more extended and accurate data set.

The composite color-color diagrams derived from similar passbands show a statistically good correlation, with few discrepant cases.

The IRAS [12]−[25] and WISE 12−22 ($W3$−$W4$) colors show an overall satisfactory correlation in spite of the spread of 0.6 mag in the IRAS color of the non-variable stars while the same stars are grouped in just 0.2 mag in the WISE color (see x axis of Figure 3 and Figure 2). The two most discrepant cases are the large amplitude, irregular variables BIS 207 and 198, 0.3 mag away from the ridge line.

The number of BIS sources present in the AKARI database is smaller than in other databases and for these stars only the fluxes at 9 and 18 μm are available. In spite if this, the AKARI fluxes can be used in composite diagrams that give equally interesting results. The AKARI color S09−L18 correlates very well with the similar IRAS [12]-[25] color (r=0.80); only BIS 255 is definitely out (0.6 mag) of the correlation. This star, however, is not peculiar in the IRAS [25]–[60] vs [12]–[25] plot (Figure 3) and is not variable.

The correlation of AKARI S09−L18 with the WISE 12−22 color is even better (r=0.90), again with BIS 255 standing out (0.6 mag): in this plot also BIS 007 (which anyhow is a Mira-type star) is markedly out (0.3 mag) of the correlation; both stars have a good quality flag in the AKARI catalog and are positioned near the ridge line in the 12−22 ($W3 - W4$) vs 4.6−12 ($W2 - W3$) WISE color-color plot.

Important diagrams applied to different passbands have been constructed and accurately studied using the AKARI database by Ishihara et al. (2011) and Ita et al. (2010); we have successfully applied the same combinations to our data. In Figure 3 of Rossi et al. (2016) we have plotted the combination proposed by Ishihara et al. (2011) K-[S09] vs [S09]-[L18], that we have compared with K-$W3$ vs $W3$-$W4$. Using J instead of K yields to similar results with even more extended range in the y axis as shown in Figure 5 of the present work. Again, the obscured carbon and oxygen-rich stars are distributed along well separated paths, and oxygen Miras lie in the upper part of the strip of variables. In

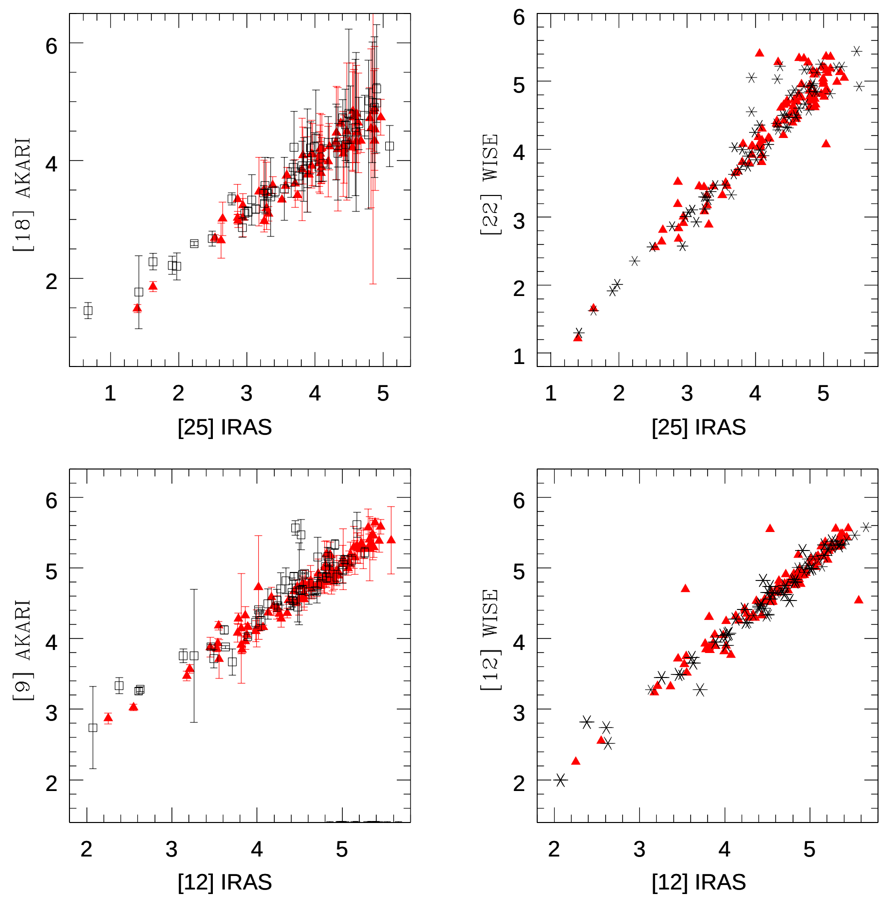

Fig. 4. Correlation between magnitudes AKARI−IRAS and WISE−IRAS. The symbols are: black stars and open squares = stars present in G17; red filled triangles = stars not present in G17. In the right panel the mean errors are 0.016 for $W3$ and 0.02 for $W4$; IRAS only provides a quality factor. The color figure can be viewed online.

the top panel the range of the sources is spread along the x axis more than in the bottom panel; for this reason [S09]-[L18] is not too effective in separating variable from non variable stars.

4. CONCLUDING REMARKS

In the present paper we have described the distribution of the BIS catalog stars in several color-color IR plots. We used the spectral classification and variability classes derived in our companion paper G17 for a subsample of BIS stars to interpret the distributions of these infrared plots.

• We used the classical $J - H$ vs $H - K$ diagram to check the luminosity class and to look for the presence of cool dusty envelopes around the stars.

• All the diagrams involving WISE colors are efficient in separating the early-M type, non-variables, from the mid- and late- type stars (all variables). The presence of emission lines in the optical spectrum is not a discriminant for the position of the stars in any of the WISE diagrams.

It is worth noticing that all the confirmed Miras have the $W1 - W2$ color greater/equal than 0.5 mag, while the other (non dusty) stars lie below this limit. The dust enshrouded carbon stars are always outstanding in all plots, aligned in a diagonal path: the naked carbon star BIS 194 falls in the group of the early O-rich stars and cannot be distinguished with these diagrams. The stable stars are clustered in the lower left (blue) corner of all plots.

• Similar results were also obtained from composite color-color diagrams. The agreement holds for optically variables too; this result is supported by the satisfactory correlation found by comparing data from different experiments. Carbon stars are always well distinguished from M stars; more remarkable is

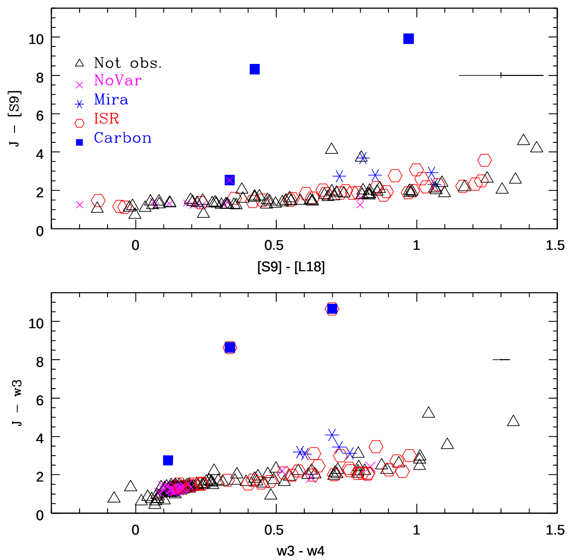

Fig. 5. Top: $J-$[S09] vs [S09]$-$[L18] color-color diagram. The errors in the x axis are typically 0.15 mag.; in the y axis the errors are due to the [S09] magnitude and are similar, but not relevant thanks to the extended magnitude range. Bottom: $J - W3$ vs $W3 - W4$ diagram. The errors are typically 0.05 mag. These values are indicated by the crosses at the corners. The color figure can be viewed online.

that the (few) confirmed Miras in every diagram are slightly but clearly separated above the strip defined by the other variables.

• We have analysed our sample in the IRAS [25]$-$[60] vs [12]$-$[25] color-color plot (Figure 3) finding only an overall general agreement with the zones defined by van der Veen & Habing (1988). While the carbon and stable stars lie in the expected regions, the irregular, large amplitude variables of M-type are distributed everywhere in the diagram. Strong discrepancies in the y axis might be attributed to the large uncertainties of the fluxes at 60 μ, but for the same stars the locations in the x axis where the quality factors are generally good (3, 2) are less obvious.

From our new optical spectra and from the infrared data we have been able to better define the populations of the BIS catalog. Among the "normal" stars of the halo population, we have also discovered few objects deserving special attention.

An outlier is BIS 010. The optical magnitudes of this optically normal M5 star are probably wrong in every catalog derived from the POSS; it is the northern component of an apparent close binary; we took a spectrum of the companion, finding a G star, extremely faint in the R band and disappearing already in the near infrared images (see G17). The peculiarity of BIS 010 is the extreme infrared brightness revealed by the WISE, IRAS and AKARI coherent magnitudes that put this star very far from the bulk in every color-color diagram, out of the scale of the plots presented in this paper, but well separated from the strip of the dusty carbon stars. In the near infrared color-color diagram the red component of BIS 010 is not peculiar with $J - H$=0.94, $H - K$=0.40, while the WISE magnitudes are $W1 = 10.3$, $W2 = 8.58$, $W3 = 4.34$, $W4 = 1.63$).

Another extremely puzzling object is BIS 131, a K2 star whose peculiarity in the optical spectrum is the presence of permitted and forbidden emission lines (Rossi et al. 2010). Our long term photometric monitoring is revealing slow, small amplitude photometric variability and minor spectroscopic variations of the emission lines (not yet published). Similarly to BIS 010, the colors of BIS 131 are normal in the optical and near IR, and extreme in the far IR.

Combining the optical information from G17 with the infrared one described in the present paper we are now in the position to make statistical predictions on the overall stellar content of the whole BIS sample. Among the 181 BIS sources still not studied in the optical, we expect that 15% are earlier than M2 while the rest are late M with few dusty M-type; a few Miras (one is already known, BIS 176) may be present. No dusty carbon star is expected, while a few CH or R carbon stars may still be present.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This publication has made use of data products from: the Two Micron All$-$Sky Survey database, which is a joint project of the University Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology; the Wide$-$field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration; the Northern Sky Variability Survey (NSVS) created jointly by the Los Alamos National Laboratory and University of Michigan; the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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