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DENIS and ISOGAL properties of variable star candidates in the Galactic Bulge*,**,***

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Abstract. Repeated DENIS observations (summer 1996 & 1998) in the J (1.25 μm) and the K_S (2.15 μm) bands are used to look for variable stars. We present two catalogues of $\sim$ 1000 probable variables in an area of $\sim 4\,\mathrm{deg}^2$ of the inner galactic bulge. The first one contains $\sim$ 720 variable star candidates which show variability in J and K_S while the second consists of sources only observed to be variable in K_S (~ 270 sources), mainly in regions with high interstellar extinction.

Using the extinction map by Schultheis et al. (1999a), most of the variable stars are found to be above the RGB tip and thus belong to the AGB while there is a small fraction of candidates which could be below the RGB tip with rather small "amplitudes" of $\sim$ 0.3–0.4 mag in K_S.

Our catalogue has been cross-correlated with five ISOGAL fields (total area $\sim 0.5\,\mathrm{deg}^2$) in order to study the mid-IR properties of the LPVs. The AGB variables can be distinguished from other M-type giants by their high 7 μm luminosities and redder $K_0 - [7]$ colours.

Based on a few repeated ISOCAM observations a good correlation is found between near- and mid-IR variability.

Key words: stars: AGB and post-AGB – stars: variables: general – ISM: dust, extinction – Galaxy: general – infrared: stars

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1. Introduction

Knowledge of the variable star content in the inner galactic bulge is of great interest since these objects are useful both as population and distance indicators. Due to their high luminosities, the long-period variable stars (such as semiregulars, Miras and OH/IR stars) are ideal tracers of the stellar populations in the inner galaxy and can be detected even in highly extincted regions.

While in the past variable star studies in the intermediate galactic bulge were mainly focused on relatively unobscured fields such as Baade's Windows (Lloyd Evans 1976, Glass et al. 1995, Glass & Alves 1999), recently several long-term monitoring programs in the highly extincted inner galactic bulge were undertaken in the near-infrared, resulting in high quality light curves. Wood et al. (1998) report a long-term K-band monitoring program of well-known OH/IR sources in the inner Bulge. Glass et al. (in preparation, herafter referred to as GMCS (Glass I.S., Matsumoto B.S., Carter B.S., Sekiguchi K.)) performed a four-year K band survey of large amplitude variable stars in a 24 x 24 arcmin^2 area centered on the Galactic Centre. Periods and amplitudes were obtained for $\sim$ 400 objects, most of them Mira variables and OH/IR stars.

The ISOGAL (Pérault et al. 1996, Glass et al. 1999, Omont et al. 1999) project has surveyed a number of fields at low galactic latitudes in the mid-IR using the ISOCAM (Cesarsky et al. 1996) instrument of the ISO satellite. Due to its much higher sensitivity and spatial resolution compared to IRAS, the ISOGAL survey permits us to study the stellar content of the inner Galaxy, even in the presence of high obscuration.

Omont et al. (1999) have studied a field in the inner galactic bulge ($\mathrm{l} = 0^0$, $\mathrm{b} = +1^0$) with relatively low and homogeneous extinction. Analysis of the sources at five wavelengths covered by ISOGAL and DENIS shows that the majority of them are red giants with luminosities just above or close to the RGB tip. In colour-magnitude diagrams such as [15]/[7]–[15] and $[15]/\mathrm{K_S} - [15]$ they form a mass loss sequence starting with red giants having low mass-loss rates and rising up to high mass-losing AGB stars.

Glass et al. (1999) analysed the mid-infrared properties of M giants and Mira variables in Baade's window using ISOGAL data. They found that Miras are more luminous at 7 μm and have redder K-[7] colours than other M giants.

Glass, Alves and the ISOGAL and MACHO teams (1999) obtained MACHO lightcurves in V and R for approximately 300 of the ISOGAL objects in Baade's windows that were found by Glass et al. (1999). Similar information should exist in the databases of the OGLE (Udalski et al. 1997) and EROS (Derue et al. 1999) collaborations. Nearly all these sources were classified as semiregular variables with weak amplitudes and short periods, which are many times more numerous than Miras, with mass-loss rates from about a few $10^{-9}\,\mathrm{M_\odot\,yr^{-1}}$, to $\sim 10^{-7}\,\mathrm{M_\odot\,yr^{-1}}$ for periods in excess of $\sim$ 60 days.

In this paper we present a catalogue of $\sim$ 1000 Variable Star candidates in the inner bulge ($-4^0 < \mathrm{l} \lesssim +1^0$ and $|\mathrm{b}| \lesssim 1^0$, see Fig. 1), based on repeated DENIS observations (1996 & 1998). The majority of these sources are long period variables on the AGB with large "amplitudes". We will discuss further in detail the near and mid-IR properties of these variable candidates as revealed by ISOGAL data including repeated ISOCAM observations.

2. Observations

2.1. DENIS observations

The near-infrared data were acquired in the framework of the DENIS survey (Epchtein et al. 1997), as part of a dedicated observation of a large Bulge field in the three usual bands, Gunn-I (0.8 μm), J (1.25 μm) and $\mathrm{K_S}$ (2.15 μm).

Specific regions in the inner galactic bulge (see Fig. 1) were observed in the 1996 and 1998 seasons. Unfortunately, the data from several fields observed during 1996 were of bad quality (either poor photometry or missing images). These were not included (see Table 1) in the analysis that follows which is limited to the fields displayed in Fig. 1.

An area of $\sim 4\,\mathrm{deg}^2$ was used for all variable star searches in the J and $\mathrm{K_S}$ bands. As seen in Fig. 1 there is a small overlap with the field observed by GMCS. Table 1 gives the journal of the DENIS observations.

For the source extraction we used PSF fitting optimised for the crowded fields (Alard et al. in preparation). The DENIS astrometry has been performed using the USNO-A2.0 catalogue (Monet et al. 1998) as a reference. The absolute astrometry is then fixed by the accuracy of this catalogue ($\sim 1''$). The internal accuracy of DENIS observations, derived from the identifications in the overlaps, is of the order of 0.5$''$.

For the determination of the zero points all standard stars observed in a given night have been used. The typical uncertainty of the zero points has been derived from the overlapping regions and is about 0.05, 0.15 and 0.15 mag in the I,J and $\mathrm{K_S}$ bands respectively.

Table 1. Journal of repeated DENIS observations in the Inner galactic Bulge.

Identification	Filter	Obs. date	Remarks
C01$^{(a)}$	IJK	08/04/96	
C02$^{(a)}$	IJK	31/03/96	
C03$^{(a)}$	IJK	02/04/96	
C04$^{(a)}$	IJK	11/04/96	
C05$^{(a)}$	IJK	12/04/96	GMCS field
XGAL1734B$^{(a)}$	IJK	28/08/98	
XGAL1737B$^{(a)}$	IJK	29/08/98	
XGAL1740B$^{(a)}$	IJK	18/05/98	
XGAL1743B$^{(a)}$	IJK	06/06/98	GMCS field

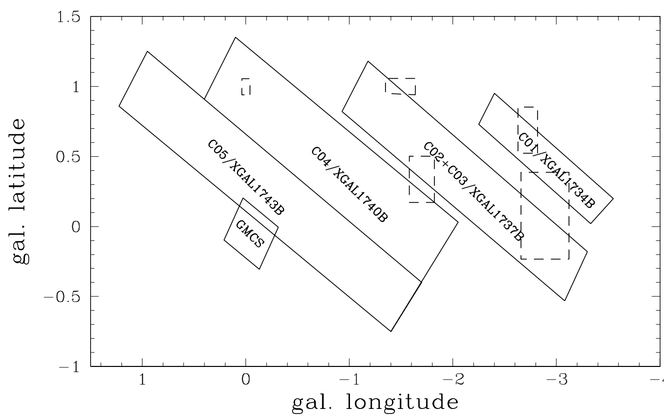

Fig. 1. Galactic coordinates of DENIS fields which were observed in summer 1996 & 1998. The field of GMCS (in preparation) near the GC is also shown. The dashed areas indicate the ISOGAL fields with LW2 and LW3 observations.

We do not make use of the DENIS data with $\mathrm{J} < 8$ or $\mathrm{K_S} < 7$ due to saturation of the detectors.

2.2. Extraction of variable star candidates

For each DENIS field where repeated observations exist (see Table 1 and Fig. 1), the two corresponding DENIS catalogues (i.e. C01 with XGAL1734B, C02 and C03 with XGAL1737B, C04 with XGAL1740B and C05 with XGAL1743B) have been cross-correlated using a small search radius of $2''$ to avoid misidentifications.

The offset in the photometric zero point in J and $\mathrm{K_S}$ between the observations obtained in 1996 & 1998 is for each field less than 0.15 mag for $8^\mathrm{m} < \mathrm{J} < 14^\mathrm{m}$ and $7^\mathrm{m} < \mathrm{K_S} < 10^\mathrm{m}$, respectively. The rms of each of the fields (see Fig. 1) is 0.16 mag in J and 0.14 mag in $\mathrm{K_S}$. Fig. 2 shows one typical variable star field (C04/XGAL1740B) where the residual is shown as a function of magnitude.

Due to the huge amount of data (the corresponding DENIS catalogue contains about 450,000 sources) a search by eye for variable star candidates is not possible. In order to minimize false detections the following selection criteria have to be fullfilled for a candidate to be regarded as a likely genuine variable star:

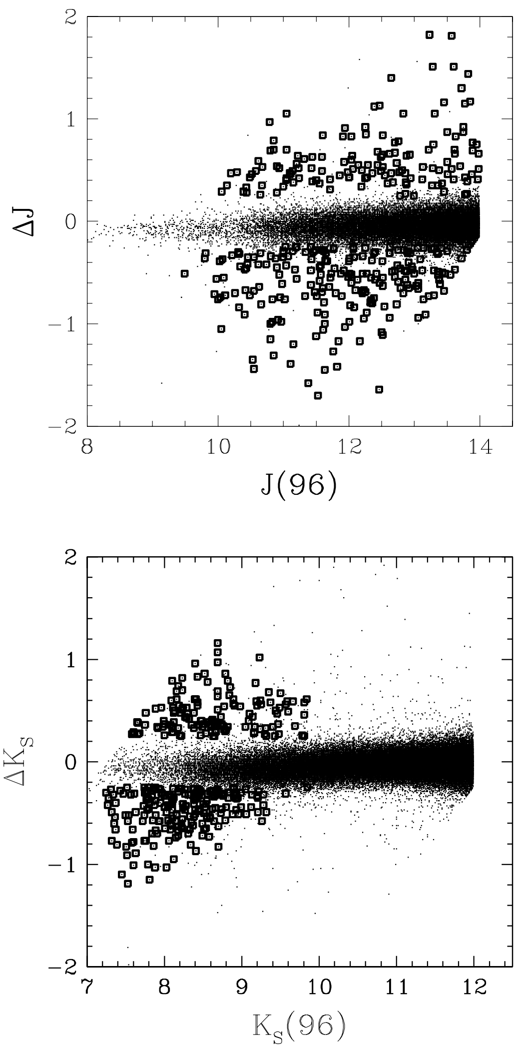

Fig. 2. Variable star field C04/XGAL1740B: Upper panel: Differences in J between 1996 and 1998 observations. The rms error is 0.16 mag in J and 0.14 mag in $\mathrm{K_S}$. Suspected variable stars (variable in J & $\mathrm{K_S}$) are indicated by open squares. Lower panel: Same as upper panel but for the $\mathrm{K_S}$ filter

1. $8 < \mathrm{J} < 14$ and $7 < \mathrm{K_S} < 10$ mag
2. Detection in ΔJ and $\Delta\mathrm{K_S}$ above $2\,\sigma$ level.
3. The magnitude differences (ΔJ and $\Delta\mathrm{K_S}$) in the two filters must have the same sign.

The result is a catalogue of 721 variable star candidates in an area of $4\,\mathrm{deg}^2$. Fig. 2 shows the variable star candidates for the field C01/XGAL1740B indicated by open squares. Due to the saturation limit of $\mathrm{K_S} \sim 7$ and the high interstellar absorption, the brightest variable stars detected in J are ~ 10.5 mag while in $\mathrm{K_S}$ they are in the range 7–9.5 mag. About 2% of the variable sources did show an opposite sign in ΔJ and $\Delta\mathrm{K_S}$ and therefore had to be rejected. A detailed discussion about the reliability of our variable candidate sources can be found in Sect. 2.3

As shown by Schultheis et al. (1999a), there is a large proportion of the sources detected at $\mathrm{K_S}$ which do not have DENIS counterparts at the shorter wavelengths in highly obscured regions ($\mathrm{A_V} > 25^{\mathrm{m}}$). Thus the catalogue is biased against stars in highly extincted regions. For this reason we also looked for such stars which are variable only in $\mathrm{K_S}$. A problem for these sources is that we have no independent criteria that can be used to distinguish between real variable stars and spurious selections. A comparison with the field by GMCS shows (see section below) that if one adapts an upper limit of $\mathrm{K_S} < 10$, the number of spurious selection is small. When taken together with a detection in $\Delta\mathrm{K_S}$ above the 2σ level, 642 possible variables are found. 371 ($\sim 58\%$) of these have a non-variable J counterpart ($\mathrm{J} < 14^{\mathrm{m}}$) at $2\,\sigma$. We do not regard these sources as variable stars as we expect them to be also variable in J. Thus, an additional catalogue of 271 possible variables in $\mathrm{K_S}$ is obtained. Nevertheless, the proportion of spurious variables remains $\sim 20\%$ (see section below).

2.3. Reliability check – comparison with the GMCS field

As shown in Fig. 1 there is only a small overlap with the GMCS field. Their sample of large-amplitude variable stars based on a four-year K-band monitoring program is complete up to K $\sim 10^{\mathrm{m}}$. We took it as a reference field to check the reliability of our catalogue and to get an independent view on the DENIS photometry.

The catalogue of GMCS contains in total $\sim$ 400 identified long period variables with the position, the mean K magnitude, the period and the amplitude in $\mathrm{K_S}$. The amplitude range is between 0.25 mag and 2.9 mag. Ninety-two of them overlap our variable star field while 74 of them are brighter than 10^{m} in K. Cross identification with DENIS (see Fig. 3) shows that the DENIS $\mathrm{K_S}$ photometry is in very good agreement (the modal value is ~ 0.05 mag) with those obtained by GMCS. Based on observational near infrared spectra for a sample of M giants and Mira variables, kindly provided by A. Lançon, the difference between K and $\mathrm{K_S}$ is estimated to be of order of 0.03–0.05 mag. Thus, there remains only a very small and negligible difference between DENIS and GMCS photometry. The wide spread in the distribution of Fig. 3 is mainly due to the large "amplitude" variation of the AGB stars (see e.g. the amplitude range of GMCS variables mentioned above) as we have (in contrast to GMCS) only randomly phased, double-epoch, observations.

Cross identification between our variable star catalogue and the GMCS catalogue shows that out of the 74 GMCS variable stars we find 4 variable in J & $\mathrm{K_S}$ and 10 only in $\mathrm{K_S}$. The relatively small number in the J & $\mathrm{K_S}$ detection compared to the $\mathrm{K_S}$ detection is due to the high interstellar extinction in this field ($\mathrm{A_V} > 30^{\mathrm{m}}$). Thus, in highly extincted regions we can recover only $\sim$ 20% of the variable stars which is mainly caused by our strict selection criteria (see section above) for avoiding spurious variables. Due to the large amplitude variation of the GMCS variables, an additional fraction of the variables ($\sim$ 20%) will end up outside of our $\mathrm{K_S}$ magnitude range ($7 < \mathrm{K_S} < 10$), depending on their pulsational phases at the DENIS epochs. Taking this into account, ~ 40% of the GMCS variables are recovered or outside the range of our research. The remaining

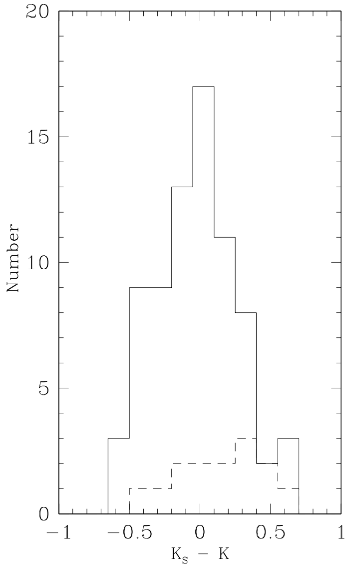

Fig. 3. Comparison between K photometry by GMCS and K_S (1998) obtained by DENIS. The dotted line indicates those GMCS variables which are found to be variable in DENIS. The modal value of the distribution of the difference $K_S - K$ is $0^m.05$. Note that in contrast to GMCS the K_S filter has been used.

60% are not recovered mainly due to unfavourably small phase differences between the two DENIS epochs for these stars.

As already mentioned above, emphasis has been placed on the reliability of our variable star candidate sources. A comparison with the GMCS results should be a good indicator (assuming that this catalogue is complete) of the portion of spurious sources we have to expect. In the overlap area, no additional variable sources in J & K_S has been found while 3 of the K_S variables were not detected by GMCS. Assuming that the sample of GMCS is complete ($K < 10^m$), we estimate that $\sim 20\%$ of the variable star candidates are most likely spurious cases or eventually possible low "amplitude" variables (Glass & Alves 1999). Additional repeated observations are necessary.

2.4. The catalogues of variable star candidates

The final catalogues of the variable star candidates consist of 721 sources variable in J & K_S and 271 only in K_S. These catalogues are available in electronic form at the CDS via anonymous ftp from *cdsarc.u-strasbg.fr*. They are in the following format (see Table 2):

Column 1 gives the identification number, column 2 and 3 the DENIS equatorial coordinates in degrees (J2000), columns 4 and 5 the galactic longitude and latitude, columns 6–8 the DENIS IJK_S photometry and columns 9–10 the magnitude difference in the J and K_S filter between Summer 1996 and Summer 1998 observations.

Table 2. Format of the catalogues of the variable star candidates

Column	Name	Description	Unit
1	Number	DENIS-V*hhmmss.s-ddmmss*	
2	Ra	Right ascension at the epoch 2000	[^{0}]
3	Dec	Declination at the epoch 2000	[^{0}]
4	l	galactic longitude	[^{0}]
5	b	galactic latitude	[^{0}]
6	I	mean I magnitude	[mag]
7	J	mean J magnitude	[mag]
8	K_S	mean K_S magnitude	[mag]
9	ΔJ	Difference in J mag	[mag]
10	ΔK_S	Difference in K_S mag	[mag]

Table 3. Journal of ISOCAM observations with LW2 and LW3 observations covered by the repeated DENIS observations (see Fig. 1 and the ISOGAL Webpage under http://www-isogal.iap.fr)

Identification	Filter	Pixel Size	Julian Date	(l,b)
32500238	LW3	$6''$	2450363	-1.49+01.00
83701309	LW2	$6''$	2450874	-1.49+01.00
49701701	LW2	$6''$	2450535	-1.70+0.34
31900202	LW3	$6''$	2451185	-1.70+0.34
49701702	LW2	$6''$	2450535	-2.72+0.69
49701770	LW3	$6''$	2450535	-2.72+0.69
50701205	LW2	$6''$	2450545	-2.89+0.16
31100401	LW3	$6''$	2450349	-2.89+0.16
32500256	LW2	$6''$	2450363	0.00+01.00
13600327	LW3	$6''$	2450174	0.00+01.00
83600418	LW2	$6''$	2450873	0.00+01.00
83600523	LW3	$6''$	2450873	0.00+01.00

2.5. Variable stars in ISOGAL

In the regions covered by the variable star catalogues in the near-IR (see Fig. 1), LW2 (5.5–$8\,\mu$m) and LW3 (12–$18\,\mu$m) observations for five ISOGAL fields exist. Table 3 gives the journal of the ISOCAM observations.

In addition to the usual problems with the ISOCAM data (glitches, dead column, time dependent behaviour of the detectors), the difficulties of reduction of the ISOGAL data are more than usually severe due to the crowding in these fields, the high density of bright sources which induce long-lasting pixel-memory effects, the highly structured diffuse emission, etc.. Therefore a special reduction pipeline was devised (Alard et al., in preparation) which is more sophisticated than the standard treatment applied to ISOCAM data. A more detailed discussion of the data reduction and data quality can be found in Omont et al. (1999).

There are only a few *repeated* ISOCAM observations of ISOGAL fields at different epochs. In the area covered by the DENIS variable star candidate catalogue there is only one ISOGAL field, located at $l = 0^0$ and $b = 1^0$ (see Omont et al. 1999 for further details), with repeated observations (performed with $6''$ pixels) at two different dates (see Table 3) in both LW2 and LW3 filters.

2.6. Variability criterion for ISOGAL sources

We here consider that a source is a candidate variable when there is a 3σ difference in one band, or consistent weaker indications

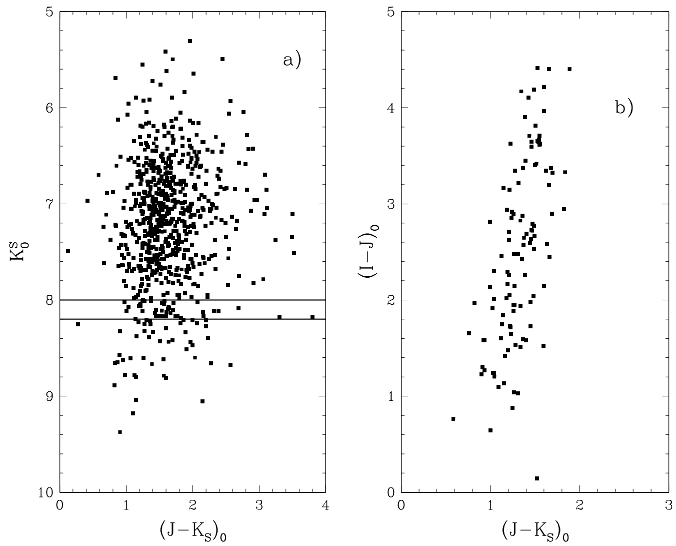

Fig. 4a and b. Colour-magnitude and colour-colour diagram of the variable star candidates which are variable in both J and K_S. The data have been approximately dereddened using the extinction values of Schultheis et al. (1999a). The approximate position of the RGB tip is shown by the solid lines at $K_0 = 8.2$ (Tiede et al. 1996) and $K_0 = 8.0$ (Frogel et al. 1999)

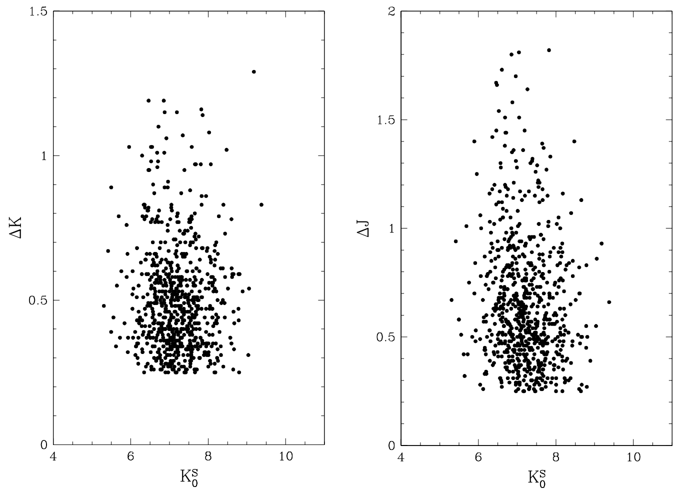

Fig. 5. ΔK_S and ΔJ of the variable star candidates which are variable in both J and K_S as a function of the dereddened K_S mag.

in both bands. In what follows, only sources variable in both LW2 and LW3 filters were considered to be confirmed variables. LW2 had to be brighter than 9.5 and LW3 < 8. Thirty sources fullfill these criteria.

We used for the cross-identification between DENIS and ISOGAL well established standard routine procedures which are described in Omont et al. (1999)

3. Variable stars in the near-infrared

The $K_S/J-K_S$ colour-magnitude diagram (CMD) and the $(I-J)/(J-K_S)$ colour-colour diagram are powerful tools to study the stellar populations in the galactic Bulge (see e. g. Frogel et al. 1999, Omont et al. 1999, GMCS, Schultheis et al. 1998). In most parts of the galactic bulge, the study of stellar populations is hampered by high interstellar absorption which is clumpy rather than homogeneous (Frogel et al. 1999, Catchpole et al. 1990, Schultheis et al. 1999a). Recently, Schultheis et al. (1999a) mapped the interstellar extinction of the inner galactic bulge ($\sim 20\,\mathrm{deg}^2$) using DENIS observations in the J and K_S bands together with isochrones calculated for the RGB and AGB phase. We have used this extinction map to obtain dereddened CMD and colour-colour diagrams for the variable star candidates, as shown in Fig. 4. Note that in highly obscured regions ($A_V > 25^m$) Schultheis et al. (1999a) obtained only a lower limit to A_V due to the problem of “missing J sources” (see their paper for details).

Most of the variable star candidates which are variable in both J and K_S are located above the tip of the bulge RGB ($K_0 \sim 8.2$, Tiede et al. 1996; $K_0 \sim 8.0$, Frogel et al. 1999). These correspond to AGB stars with different intrinsic properties such as luminosity, temperature, metallicity, mass loss, pulsational behaviour, etc. We expect to find all types of variable AGB stars in our sample, such as Miras, semiregular variables (“blue”,”red” and “Mira-like” SRVs —see Kerschbaum & Hron 1994 for the distinction) and irregular variables. The wide colour range is also found in the GMCS sample and reveals the different intrinsic properties of AGB stars. Nevertheless, uncertainties in the determination of extinction (especially in regions with $A_V > 25^m$) may be responsible for at least part of the observed spread in $(J-K_S)_0$, in particular the very blue sources with $(J-K_S)_0 \lesssim 1.0$.

There are a small number of variable star candidates below the RGB tip for the bulge with $K_0 \sim 8.0$–8.2 (Tiede et al. 1996, Frogel et al. 1999). If they are real variables and not located behind the bulge, these stars might be RGB stars or, as the AGB extends well below the RGB tip, less luminous AGB stars with small “amplitudes” (∼ 0.3–0.4 mag in K_S). For these stars a systematically slightly lower ΔJ and ΔK_S has been found compared to the variable AGB stars as shown in Fig. 5. Nevertheless, additional observations are required in order to exclude the possibilty of spurious sources.

The colour-colour diagram (see Fig. 4b) shows that while $(J-K_S)_0$ is confined to a very small range ($\sim 1\,\mathrm{mag}$), there is a wide range in $(I-J)_0$ colour due mainly to a large spread in I magnitudes of the bulge AGB giants, exceeding 3 magnitudes (see also Frogel & Whitford 1987, Schultheis et al. 1998). Synthetic spectra using new improved model atmospheres of AGB stars (e. g. Aringer et al. 1999) using all relevant molecular opacities of H_2O, CO, TiO, VO, etc. can now reproduce this wide colour range in $(I-J)_0$ (Schultheis et al. 1999b).

4. Near- and mid-infrared properties of variable star candidates

As mentioned in Sect. 2.5, five ISOGAL fields (with observations in the LW2 and LW3 filter) cover parts of the variable star field. In what follows we used for each of the five ISOGAL fields the final DENIS-ISOGAL catalogue which contains (besides

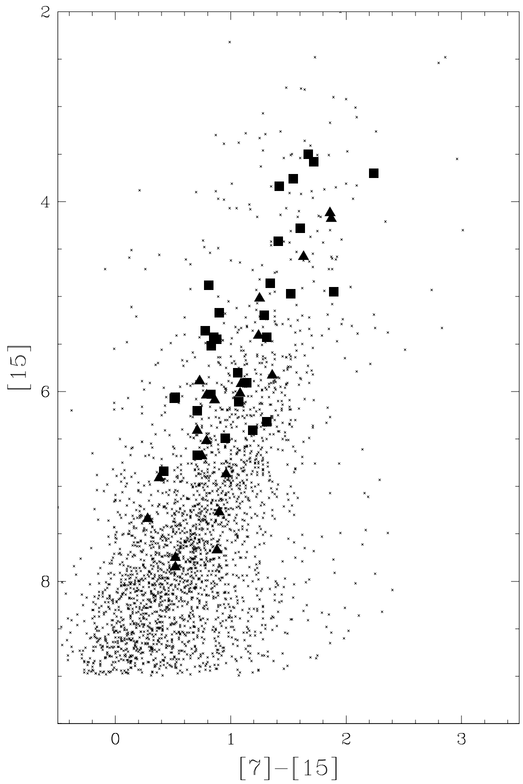

Fig. 6. Combined [15]/[7]-[15] magnitude-colour diagram of ISOGAL sources for five ISOGAL fields listed in Table 3. Stars "variable" in J and K_S are indicated by filled squares while stars "variable" only in K_S are denoted by filled triangles

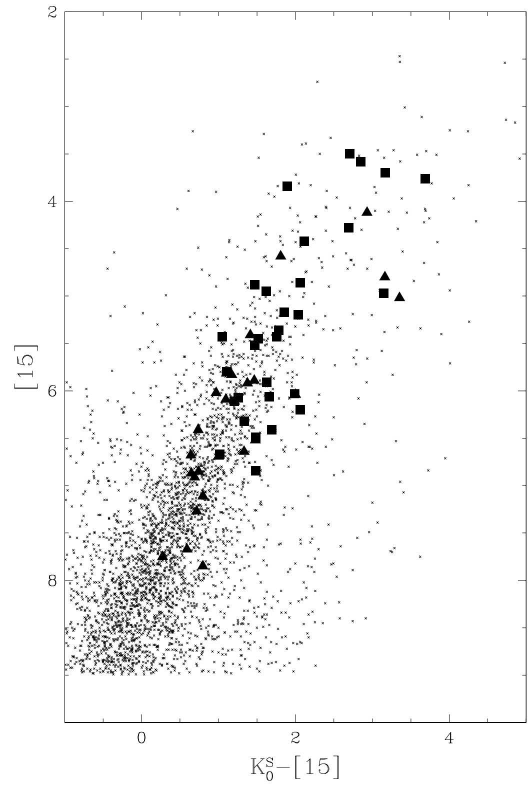

Fig. 7. Combined $[15]/(K_0^S - [15])$ diagram of ISOGAL sources for five ISOGAL fields. Symbols are the same as in Fig. 6. The sources were dereddened using the extinction map of Schultheis et al. (1999a)

the accurate coordinates provided by DENIS) the five filters (I,J,K_S,LW2,LW3). These catalogues have been merged and cross-identified with the two variable star catalogues (i. e. stars variable in both J & K_S and those variable only in K_S). Fig. 6 shows the [15]/[7]-[15] diagram of the merged catalogue of all five ISOGAL fields together with the variable star candidates.

As pointed out by Omont et al. (1999) and Glass et al. (1999) the majority of the sources form a mass-loss sequence of RGB/AGB stars located in the galactic bulge. Figs. 6 and 7 show that there is a steady increase of mass-loss from the non-variable, mid-M giants to the LPVs. Omont et al. (1999) showed that the tip of the RGB corresponds to $K_0 - [15] \sim 0$ or $[15] \sim 8$ which means that most stars brighter than ~ 8.0 are on the AGB. The majority of variable stars having an ISOGAL counterpart are located on the AGB.

The majority of variable stars show a large 15 μm excess ($K_0^S - [15] > 1$) corresponding to AGB stars with a relatively large mass loss rate ($\geq 10^{-8}\,M_\odot/yr$)

The [7]–[15] colours of the variable star candidates are on average slightly displaced from the Bulge sequence of the late M-stars towards a bluer [7]–[15] colour. A similar result has been obtained by Glass et al. (1999) for the Mira variables in Baade's window. Unlike the late-type giants, where the contribution at 7 μm is small, the dust contributes to both the 7 and 15 μm bands for optically thick Miras. The reason for the bluer colour may be that the dust emission in Miras, which have relatively thick silicate shells, may be stronger in the 7 μm band than at 15 μm, when compared to the SR variables. Additional absorption from the CO_2 band at 15 μm (Onaka et al. 1997) and the Al_2O_3 feature at 13 μm (Kozasa & Sogawa 1998, Sogawa & Kozasa 1999) may also be partly responsible for this effect.

The large scatter in the [7]–[15] colours ($\sim 1\,mag$) for the variable star candidates (see Fig. 6) is most likely due to variation of the circumstellar dust emission around an oxygen-rich Mira over an entire light variation cycle (Onaka et al. 1998). In addition, the LW2 band is strongly affected by the SiO fundamental band at $\sim 7.9\,\mu$m (Cohen et al. 1995). Aringer et al. (1999) showed that the strength of the first overtone bandhead between 4.0 and 4.5 μm is related to the strong pulsations which cause its variablity. Large amplitude variables such as Miras therefore show a very large scatter of the equivalent widths of the SiO bands (they can disappear around the time of light maximum, see their Fig. 7).

The $[7]/K_S - [7]$ diagram seems to be the best criterion for the detection of large-amplitude LPVs (Glass et al. 1999). Fig. 8 shows that almost all suspected variable stars are completely distinguishable from other stars by their rather large 7 μm excess. As the dust emission at 7 μm is responsible for the large $K_S - [7]$ values, we identify them as LPVs on the AGB with a large mass loss rate ($\dot{M} \gtrsim 10^{-7} M_\odot$/yr), see Omont et al. (1999). As mentioned above, our catalogue of suspected variable stars (see Sect. 2.3) is only complete up to the $\sim 20\%$ level because

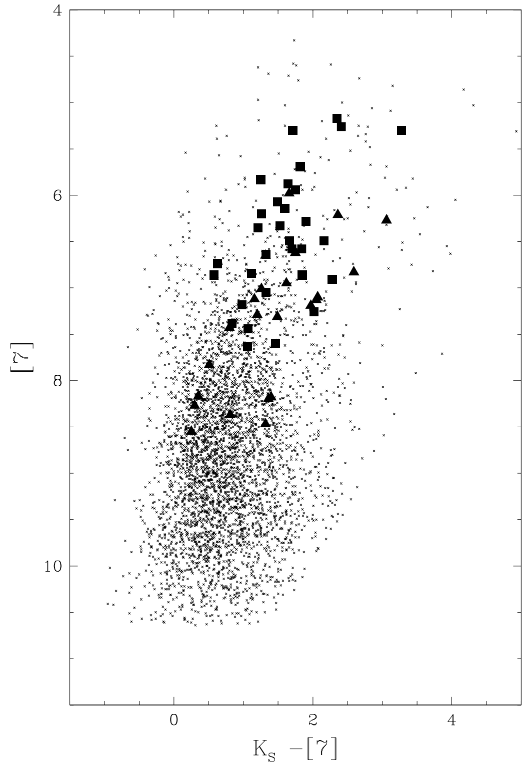

Fig. 8. Combined $[7]/(K_S - [7])$ diagram of ISOGAL sources for five ISOGAL fields. Symbols are the same as in Fig. 6. The suspected variable stars are almost completely distinguishable from other stars by their bright 7 μm mags.

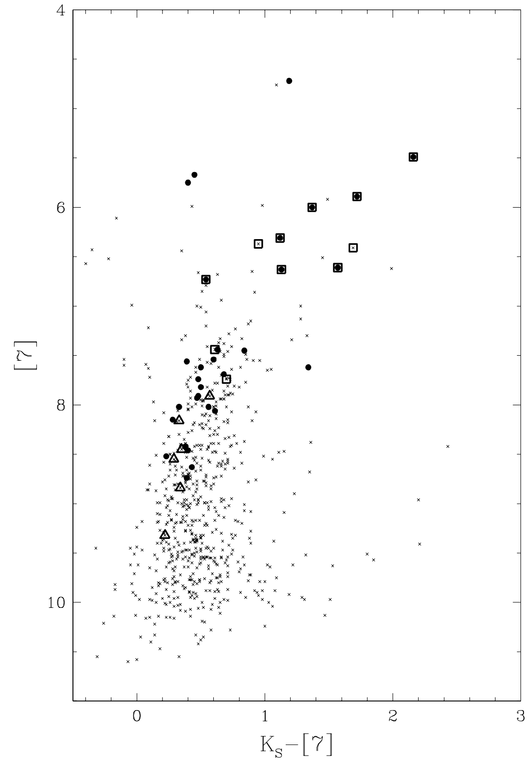

Fig. 9. Combined $[7]/(K_S - [7])$ diagram of ISOGAL sources for the C32 field ($l = 0^0, b = +1^0$). Open squares indicate sources "variable" in $J\&K_S$, open triangles "variable" stars in K_S and filled circles sources "variable" in LW2 & LW3. Sources "variable" in DENIS and ISOGAL are indicated by filled squares.

we have DENIS observations at two different epochs only. We expect therefore that nearly all sources with $LW2 < 7$ and $K_S - [7] \gtrsim 1.0$ are LPVs (see Fig. 8). Due to the uncertainty of the interstellar extinction at 7 μm Figs. 8 and 9 have not been dereddened.

A long-term monitoring program of those sources as well as of the variable star candidates are essential to confirm their long-term variability, determine their periods and classify them according to their type of variability (Mira-type, Semiregulars, Irregular Variables).

4.1. ISOGAL-DENIS variability

There is one ISOGAL field located at $l = 0.^0 00$ and $b = 1.^0 00$ with repeated DENIS and ISOCAM observations (see Table 3 and Omont et al. 1999). Fig. 9 shows that there is a good correspondance between DENIS and ISOGAL variability. For the 11 sources found to be variable in J and K_S, 7 are also variable in ISOGAL ($\sim 64\%$). The three bright variable ISOGAL sources ($[7] < 6.0$) where no DENIS variability has been found (see Fig. 9) are brighter than the DENIS saturation limit ($K_S \sim 7$). Those sources have been excluded from our search for variable stars. This high percentage compared to the low detection rate in finding stars variable in DENIS ($\sim$ 20%) is mainly due to the large "amplitudes" of the ISOGAL variables. Thus, we expect to recover most of the large-amplitude variables such as Miras while only a small fraction of low-amplitude variables (semiregular variables).

This result strengthens the argument that most of the bright 7 μm sources ($[7] < 7$) are LPVs showing strong variability in the near and mid-IR.

The remaining 20 variable star candidates in ISOGAL fields with $[7] > 7$ do not show any variability in the near-IR. The reliability of the variability of these sources has to be questioned because the uncertainty in the ISOGAL photometry increases for faint sources (see Omont et al. 1999 for the discussion about ISOGAL photometry).

5. Conclusion

Based on repeated DENIS observations in 1996 & 1998 we present two catalogues of variable star candidates of the inner Galactic Bulge in an area of $\sim 4\,\mathrm{deg}^2$, namely, a catalogue consisting of stars variable in both J and K_S with 721 entries and a catalogue of stars variable only in K_S of 271 sources. A comparison with the LPVs of GMCS shows that we find $\sim 20\%$ of the variables in their sample. The extinction map by Schultheis et al. (1999a) was used to construct dereddened near-infrared colour-magnitude and colour-colour diagrams of the variable stars. Most of the variable stars are above the RGB tip and are therefore on the AGB. There remains a small portion of variable stars which may be located on the RGB. They show systematically lower “amplitudes”. A monitoring program is essential to verify their variability.

Cross-correlation with ISOGAL fields in the inner bulge confirms that the $[7]/\mathrm{K_S}-[7]$ diagram is best suited to identify LPVs. They are bright at 7 μm and most of them have $\mathrm{K_S}-[7] \gtrsim 1.0$. We associate them with LPVs on the AGB with a large mass-loss rate.

Analysing repeated ISOCAM observations in a field at $\mathrm{l} = 0.00, \mathrm{b} = +1.00$ (see Omont et al. 1999) shows a remarkable good correlation between near and mid-IR variability. Although we are only dealing with double epoch observations in DENIS and ISOGAL, 65% of the near-IR variable stars show also variability at 7 and 15 μm.

The final catalogue of variable stars in the inner galactic bulge forms a template for a long-term monitoring program of these sources. Their pulsational period together with their type of variability —such as semiregular variables, irregular variables and Miras— will provide us with new insight into the properties of AGB stars in the Inner Galactic Bulge.

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