Asymptotic Giant Branch Stars
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Results on AGB Stars from Infrared Surveys

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Abstract. In the last 3 decades, infrared surveys have discovered new classes of AGB stars, and significantly improved our knowledge of their statistical and physical properties, often in conjunction with surveys in other spectral ranges (mainly OH maser lines). After a short description of the major past and present infrared surveys and their most commonly used analysis tools, their impact is illustrated by a few examples such as the characterisation of the populations of the Bulge and Magellanic Clouds and the distribution of carbon-rich stars in the galactic disc. In conclusion, further all-sky surveys in the still unexplored spectral regions between 2 and 10 μm are strongly advocated as well as the development of ground-based telescopes dedicated to deeper surveys and monitoring of the variability.

1. Introduction

Large scale sky surveys are often at the basis of a major breakthrough in our knowledge of the structure and evolution of stars, galaxies and the Universe in general. They increase the sample of objects that belong to previously known classes, and consequently improve our knowledge of the statistical properties of these classes (e.g., their spatial number density distribution, luminosity/mass function, evolutionary status, variability properties, etc.). They discover, often unexpectedly, sets of objects with unknown properties that turn out to form new classes (e.g., pulsars, protostars, brown dwarfs, OH/IR sources, etc.). Finally they provide calibrated maps, either directly (isoflux maps), or through star counts (isoextinction maps). Surveys generally result in an assemblage of relatively scarce, but homogeneous, information for a great number of objects, preferably spread over large areas of the sky. Resulting data are gathered into photometric *catalogues* of up to billions sources measured through a limited number of wide-band filters. These catalogues must be exhaustive down to a given magnitude which defines the *completion* limit, and the existence of a source must have a high level of *reliability* down to this magnitude limit. In addition, they must be homogeneously calibrated, and the completeness limit must be as uniform as possible across the observed target. Most useful large scale surveys involve observations in at least two colours, or better in three or more colours. Two–colour surveys (e.g., the TMSS) allow the discrimination of unusually red objects and drawings of colour–magnitude diagrams, while three-(or more) colour surveys allow the design of colour–colour diagrams, the basic tools for the analysis of a photometric survey. I will essentially focus this review

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on near–infrared (hereinafter NIR) and mid-infrared photometric surveys of the full sky (or, at least, very large fractions of the sky) with a special attention to the currently on–going 2 micron surveys, DENIS (Deep Near Infrared Survey of the Southern Sky) and 2MASS (2 Micron All–Sky Survey).

2. Major infrared sky surveys

The major IR surveys covering at least half of the sky, and performed in at least 2 bands are listed in Table 1. They are briefly described in this section. More details on the history of IR surveys can be found in the excellent reviews by Price (1988, 1997).

Table 1. Past and on–going major astronomical infrared surveys

Year[a]	Name	λ (μm)	Sensitivity (magnitude)	Sky coverage	Number of sources	Major discoveries (AGB stars)
1965 1969	TMSS	0.85; 2.2	$\sim$+3.5 (@ K)	+90° to -35°	$\sim$ 5500	dusty envelopes of LTS, IRC +10216
1970 1976	AFGL[b]	4.2; 11.0 19.8; 27.4	$\sim$+1.3 (@ 4.2 μm)	$\sim$ 70%	$\sim$ 2000	extreme AGB stars AFGL 3068; 2688...
1983 1986	IRAS	12,0; 25,0 60.0, 100.0	$\sim$ +5.0 (@ 12 μm)	$\sim$ 95%	$\sim$ 250,000[c]	first all sky IR survey IR spec. class. (LRS)
1989 1990	DIRBE (COBE)	1.25 to 240	–	all-sky	–	Bulge shape bar(?)
1996 2001	DENIS	0.80;1.25 2.15	see Tab. 2	Southern sky	$\sim 10^9$(I)	complete census of galactic and Magel-
1997 2001	2MASS	1.25;1.65 2.15	see Tab. 2	all sky	a few 10^8	lanic AGB stars
1996 1999	MSX	8.3 to 21.4	$\sim$ +7 (@ 10μm)	gal.plane Mag. Clouds	$\sim 10^6$	improve IRAS data in crowded areas

[a]in col. 1, first year refers to the beginning of the mission, and second, to the publication of the main catalogues

[b]space missions are underlined

[c]in the Point Source Catalog

The Two Micron Sky Survey (TMSS) and its associated catalogue the IRC mark the first important step in our modern knowledge of the infrared sky (Neugebauer & Leighton 1969). It discovered a few hundreds of new very red objects (Kleinmann & Payne–Gaposchkin 1979) and most importantly demonstrated that late-type giant stars are often surrounded by a thick envelope of dust which had prevented their detection so far. The most archetypical object discovered by this survey is the famous *'unusual'* carbon star IRC +10216 (Becklin et al. 1969) in the envelope of which most of the hydrocarbonaceous molecules were

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discovered later on by radioastronomers. The TMSS gave rise to a huge number of follow–up observations and studies during the past 30 years. It remained, unfortunately, uncompleted in the southern sky during 3 decades, except for a few modest attempts such as the *Valinhos* survey (Epchtein et al. 1987).

The Air Force Geophysical Laboratory Survey (AFGL) was a series of rocket flights (Price & Walker 1976) that surveyed the sky for the first time at mid–infrared wavelengths (4-20 μm). In the AGB star domain, it discovered several extreme objects such as CRL (or GL) 3068 (Lebofsky & Rieke 1977), which is, as yet, the reddest carbon star ever found.

The Infrared Astronomical Satellite (IRAS) was flown in 1983 and provided the first all–sky survey at IR wavelengths (10-100 μm range) (Neugebauer et al. 1984). It gave rise to the first comprehensive catalogue of IR sources (IRAS Science Team 1988) and led to a huge number of extremely interesting new results relevant to the AGB star domain which cannot be summarized in a few lines (see e.g., the review by Beichman 1987). Of particular interest was the collection of 8-22 μm low resolution spectra (LRS) (IRAS Science Team 1986; Volk & Cohen 1989; Volk et al. 1991) that provided a new stellar classification based on the strength of the dust (and gas) emission/absorption features in this spectral range (Walker & Cohen 1988; Walker et al. 1989; Sloan et al. 1998). Thanks to its sensitivity and completeness, IRAS provided an excellent data base to search for extreme late-type stars, and to investigate galactic structure parameters. To this aim it was followed up by many complementary observations at near–IR wavelengths (e.g., Whitelock & Feast 1984; Epchtein et al. 1990; Kwok & Hrivnak 1987) and in molecular maser lines (1612 MHz satellite line of OH, in particular, e.g., te Lintel Hekkert et al. 1991). It displayed the Bulge as mainly made of *'infrared stars'* (Habing 1988) and its shape. It showed also that very red mass–losing AGB stars are common and that *'a sequence'* can be delineated in colour–colour diagrams which might reflect their evolutionary status.

COBE/DIRBE is included in this list although, due to its large field of view (0.7°), it was not able (and was not designed) to pick up individual stars. The integrated flux measurements are useful to study the galactic structure and the variations of colours within the disc which can be interpreted in terms of stellar populations in the Galaxy. For instance, the Bulge emission essentially due to the red giant and AGB stars is extremely well delineated in the short wavelength bands (Arendt et al. 1994).

The Infrared Space Observatory (ISO) was not primarily intended to perform blind surveys, but substantial parts of the observing time was dedicated to cover targets of relatively large area. The ISO survey that is probably most relevant to AGB stars (excluding spectroscopic surveys that are reviewed by Barlow and Waters & Molster in this volume) is the ISOGAL program. ISOGAL is aimed at characterising the colours of point sources (at 7 and 15 μm) in several small areas that sample the Bulge and the inner disk of our Galaxy. The cross identification with the new 2 μm survey data DENIS (at IJK_s) allows to design a set of colour–colour diagrams which lead to characterise the various species of

AGB stars and to separate them from foreground red giants and Young Stellar Objects. First results of ISOGAL have been described by Pérault et al. (1996) and at this Symposium by Blommaert et al. (this volume) and Ojha et al. (poster contribution).

2MASS/DENIS. In the late eighties it became obvious that time was ripe to survey again the sky at 2 μm in order to improve the TMSS by a large factor (at least 10^4). This was made possible thanks to the release of large NIR panoramic arrays. Two projects, 2MASS (Skrutskie 1998) and DENIS (Epchtein et al. 1997; Epchtein 1998) are currently in progress and will end up in the early 2000s with the largest photometric databases ever produced in this spectral range. Their main characteristics can be compared in Table 2. At the sensitivity limit of these surveys, one may expect to detect all the AGB stars of the Galaxy and the Magellanic Clouds, except the most extreme ones (GL 3068 type). It should be noticed that the DENIS survey is the only attempt to survey the sky simultaneously in the NIR and optical (I band) ranges.

Table 2. *DENIS* and *2MASS* main characteristics

	DENIS	**2MASS**
Photometric bands	IJK_s	JHK_s
Sensitivity to point sources (3 σ)		
I,J,K_s	18.5, 16.3,14.0	-
J,H,K_s	-	17.1,16.4,15.6
Observing site (North)	-	Mount Hopkins, USA
(South)	La Silla, Chile	CTIO, Chile
Sky coverage	$\delta = +2°$ to -88°	all sky
Telescope aperture	1 m	1.3 m
Pixel size (I)	1 $''$	-
(J, H, K_s)	3 $''$	2 $''$
Image size	$12' \times 12'$	$8.5' \times 8.5'$
Position accuracy	0.6 $''$	0.5 $''$
Photometric accuracy	10 % or better	5 % (bright sources)
Completeness (at 10 σ)	0.99(goal)	0.99
Reliability (at 10 σ)	0.9995(goal)	0.9995
Survey strategy	strips 30°	tiles 6°
Status (as of Aug.98)	40 % achieved	40 % achieved (North) 15 % (South)

The Midcourse Space Experiment (MSX) is partly aimed at surveying the galactic plane (±5°) in 6 bands covering the 8 to 20 μm range, with deeper raster scans in selected regions (Price et al. 1998). This mission contributes to complete the IRAS mission by covering areas that were missed by IRAS, by extending the wavelength coverage and, above all, by improving the spatial resolution in crowded areas. This is of particular interest for the census of AGB stars in dense regions such as the galactic Bulge where IRAS was essentially confusion limited.

3. Some applications of IR survey data to AGB stars

The AGB phase is an essential step of stellar evolution, but it is still poorly understood because it involves intricate problems of physico–chemistry (molecule and dust grain formation), short lived phenomena such as mass loss, stellar winds, and far from equilibrium (thermal, mechanical, etc.), that were presented throughout this Symposium. Their high luminosity makes AGB stars excellent tracers of the stellar mass in the Galaxy. From the observer point of view, this high luminosity is a major advantage. The light can be analysed accurately even at large distances. This allows to obtain very-high-precision photometry (a few percents, see e.g. the HIPPARCOS data analysed by de Laverny et al. 1998), high angular resolution imagery (see the review by Lopez in this volume), high resolution spectroscopy, proper motions and derived distance measurements, and spatial distribution determinations in the solar neighbourhood (e.g., Knapik et al. 1998). One essential feature of AGB stars is that they are often surrounded by a dust (and gas) envelope (DGE) (see the complete monograph by Habing 1996) that dissipates into the ISM and enriches it with processed elements. Grains heated by the central star thermally radiate in the mid- and far-infrared. The IR range is therefore particularly well adapted to the study of AGB stars. The combination of HIPPARCOS and NIR photometric data leads to very accurate calibration of their luminosity (Alvarez et al. 1997). The NIR range is also more appropriate for high spatial resolution techniques allowing the mapping of envelopes of nearby stars (e.g., IRC +10216, Haniff & Buscher 1998). Finally, IR colour–colour diagrams and spectrophotometry (IRAS Science Team 1986) allow first-order classification of thick dust shell stars and evolutionary stages that were not previously detectable. The following Sect. is dedicated to the use and interpretations of these diagrams.

3.1. Infrared colour–colour diagrams

Near–Infrared colour–colour diagrams. A large number of JHK (LMN) photometric data have been obtained on many known AGB stars of the Galaxy, mainly Miras (e.g., Whitelock & Feast 1984) semi–regular variables (e.g., Kerschbaum & Hron 1994), carbon stars (e.g., Noguchi et al. 1981) and in the Magellanic Clouds (Sect. 3.4.). Efforts have been done also, to detect the counterparts of OH (mainly type II) maser sources which led to the new class of OH/IR objects (e.g., Hyland et al. 1972; Baud et al. 1975; Schultz et al. 1976; Glass 1978; Jones et al. 1982; Epchtein & Nguyen-Q-Rieu 1982), which are essentially an extension of the O–rich Miras towards longer periods (Le Bertre 1993), larger mass loss rates and consequently thicker dust envelopes. There are good correlations between the IR colours, the period, the 1612 MHz OH emission, and probably the mass of the star when it left the main sequence. Near IR colour–colour diagrams can be used to discriminate several types of stars such as O–rich against C–rich (Groenewegen 1998), but most accurately for objects with thick envelopes. Some confusion still remains for thin-envelope objects.

The IRAS [12–25] vs. [25–60] diagram was investigated by van der Veen & Habing (1988), and Volk & Cohen (1989) to discriminate between DGE objects with various shell opacities and chemical compositions, but some confusion remains in crowded areas of this diagram. Miras, OH/IR sources and protoplanetary nebulae are found along a sequence of increasing [12–25] index which has been interpreted as an evolutionary sequence (Olnon et al. 1984) or a sequence of increasing mass of the progenitor main sequence star (Lépine et al. 1995)

Combined near IR-IRAS diagrams (e.g., [12–25] vs. K–L). Using the results of a low sensitivity K-band survey of the southern galactic plane cross–identified with the IRAS data, Epchtein et al. (1987) have developed an efficient method of separation of C and M stars with thick DGE and showed the great reliability of the method with respect to the separation made only on the basis of IRAS colours. This method is based on the interpretation of the [12–25] vs. $[K-L]$ diagram and has been applied to pick up and classify a large number of extreme carbon stars that were not previously recognised from their optical or LRS spectra. Comparable results were recently obtained on the Magellanic AGB stars by Zijlstra et al. (1996; see Sect. 3.4.).

3.2. Mass–loss estimation from IR photometric data

Mass–loss is an essential feature of AGB stars which determines their evolution. Various semi–empirical methods have been developed based on near-infrared fluxes (Gehrz & Woolf 1971), optical CS absorption (e.g., Reimers 1977), millimetric CO emission (e.g., Knapp & Morris 1985), and far-infrared fluxes (Jura 1986). Recently, Le Bertre & Winters (1998) have shown that there is an excellent correlation of the mass–loss rate and the $[K-L]$ index. This relation holds independently for C–rich and O–rich stars. Comparable results are obtained with other NIR indices such as $[J-K]$. All-sky NIR surveys will therefore, in principle, provide an accurate estimation of the global return of matter to the interstellar medium by AGB stars.

3.3. The spatial distribution of carbon stars in the galactic disc

The exploitation of the IRC and IRAS data to derive the spatial number density distributions of AGB stars and their integrated mass–loss rate were first proposed by Claussen et al. (1987) and Thronson et al. (1987). Based on IRC data, they found a rather uniform distribution of the carbon stars up to a distance of about 1.5 kpc and a scale height of 200 pc ±50. Combining IRC and IRAS data, Jura & Kleinmann (1990) showed similar results up to a distance of about 2.5 kpc. The NIR observation of many poorly documented IRAS sources allowed Guglielmo et al. (1993, 1998) to identify a large number of new IR carbon stars (IRCS), pushing the limit of detection up to about 6 kpc and the completion distance to ≈ 4 kpc. They found a scale height of z ≈ 190 pc and a density of 22 IRCS per kpc^3 to be compared to the density of 40 kpc^{-3} found using HIPPARCOS data (Knapik et al. 1998), which includes only optical stars. The completeness limit of the IR sample is essentially given by the IRAS 25 μm sensitivity limit. The spatial density distribution of C-rich stars (optical or IR) is essentially constant in the galactic plane, but there is a deficiency of luminous carbon stars in the inner Galaxy. At large galactocentric distances, an AGB star more probably evolves towards an IRCS phase rather than through the OH/IR phase, a result that might be linked to the lower metallicity of the local interstellar medium. It is now important to keep on searching for new IRCS at larger distances to avoid biases due to the incompleteness of the samples. The combination of the 2MASS/DENIS surveys, the poorly documented IRAS sources (those many with just a 12 μm flux which cannot be classified at all), ISOGAL, and the MSX data will definitely improve our description of the spatial distribution of AGB stars in the Galaxy, and the variation of the O–rich/C–rich number density. Further important results would undoubtedly result from the projected all–sky mid–IR survey called *Next Generation Sky Survey (NGSS*; E. Wright, private communication, see Sect. 4.)

3.4. The AGB star populations of the Magellanic Clouds

The Magellanic Clouds have known distances and they are at sufficiently high galactic latitude to avoid confusion with galactic stars. So the study of the distribution and luminosity function of the AGB stars in the Magellanic Clouds is highly valuable especially to investigate the conditions of formation of the carbon–rich stars. Long-period variables in the MCs are excellent targets for the calibration of the Period–Luminosity relation of Mira and AGB stars (Hughes & Wood 1990). Optical (objective prism), and more recently photometric infrared surveys collected a large sample of Miras and AGB stars and carbon stars in the Clouds (e.g., Blanco & McCarthy 1983; Frogel & Blanco 1990; Westerlund et al. 1991; Costa & Frogel 1996). The first OH/IR star was reported by Wood et al. (1986). IRAS data have been recently exploited for a search of extreme AGB stars leading to the discovery of thick dust shell candidates (Zijlstra et al. 1996; Loup et al. 1997; van Loon et al. 1998). Preliminary K vs. $[J - K]$ colour–magnitude diagrams based on DENIS data (see Cioni et al., poster contribution, this Symposium) show that the different classes of late-type giant stars (red giants, O–rich E–AGB and TP–AGB, carbon rich AGB stars) can be easily separated. The cross–identification of these NIR data with longer-wavelength observations (IRAS, ISO, MSX) will provide an even more accurate classification and luminosity function determination (see Loup et al., this volume).

3.5. The AGB star populations of the Galactic Bulge and the inner Galaxy

The study of the late-type stellar content of the Galactic Bulge and the Galactic Center regions is essential for the understanding of the history of star formation and of the dynamical properties of the Galaxy and its central "object". Infrared observations are nevertheless strongly hampered in the most central regions by confusion due to crowding. In particular IRAS has been of little help to pick up individual stars in the inner kiloparsec. AGB star investigations in the inner Galaxy may contribute to solve some issues that deal with the star formation history near the center of the Galaxy and the metal enrichment. The Bulge population is essentially old, but a young population of long-period OH/IR stars has been singled out (Sevenster et al. 1995; Blommaert et al. 1998; Wood et al. 1998) which would argue in favour of a continuous star formation near the Galactic Center. The ISOGAL program which combines ISO data at 7 and 15 μm with DENIS data in selected areas of the Bulge will contribute to identify different populations of stars. Finally it will be of high interest to confirm (or infirm) the lack of luminous C-rich stars in the Bulge by combining near- and mid-infrared colours from DENIS/2MASS and MSX/ISO/NGSS.

4. Needs for future IR surveys

Table 3. Main future infrared space missions

Mission (countries)	Launch yr. (duration)	Covered area	Main instruments	wavelengths (μm)	Major objectives
in progress					
WIRE (USA)	1998 (4 months)	100 sq °	2 channel photometer	12 and 25	extragalactic and cosmology
SIRTF (USA)	2001 (3-4 yrs.)	observatory mode	IR camera IR spectrograph imaging photometer	3.6-10 6-40 20-180	multi objectives *Legacy program*
SOFIA (USA,D)	2001 (years)	observatory mode	Echelle spectro. FIR bolometer Mi-dIR camera	17-210 40-300 5-40	multi-objective + submillimeter heterodyne
IRIS (J)	2003 (1 yr.)	Observatory survey facility	NIR camera FIR surveyor	2-25 50-200	limited area surveys
in project					
NGSS [a] (USA)	?	all-sky survey	4 channel photometer	3-4.5;4.5-7 9-15;18-30	4-colour photometric survey
RESPIRE [b] (F)	?	all-sky survey	2 channel spectro-imager	1.8-3.6 3.6-6.5	spectrophotom. NIR survey (AGBs, ISM)

[a]Next Generation Sky Survey
[b]RElevé SPectroscopique InfraRouge Exhaustif

Large-scale NIR surveys are most valuable for the study of the physical and statistical properties of stars in general and AGB stars in particular. Even the low-sensitivity *TMSS* has been powerful enough to discover a new class of stars and detect for the first time thick dust envelopes around AGB stars. This was the starting point, together with OH surveys, of a considerable breakthrough in the understanding of mass–loss effects and gave rise to a complete renewal of the modelling of the late stages of stellar evolution towards the formation of planetary nebulae. With IRAS, DENIS/2MASS, MSX, the full sky is now covered in the short-wavelength (1-2.5 μm) and long-wavelength (8-100 μm) range with a sensitivity that allows the detection of basically all AGB stars in the Galaxy and Magellanic Clouds. Although there is no firm project aimed at performing new all–sky surveys after 2MASS/DENIS, most of the future (space) infrared missions (see Table 3) will offer some facilities to survey more deeply and re-currently selected sky areas. A large spectral window (2-12 μm) of extreme importance for AGB stars (and many other types of objects) still remains uncovered, however. There are, to my knowledge, only 2 small-size space projects that are aimed to fill this gap, the NGSS project for a 4–colour photometric survey, and a French proposal called RESPIRE which involves a 2-channel low resolution spectro–imager with special attention to survey the dust and PAHs spectral features in stellar envelopes. Although ISO has obtained a wealth of very exciting spectroscopic results in this range (e.g., reviews by Barlow and Waters & Molster in this volume), an all-sky unbiased survey such as RESPIRE would also be quite advisable for a better infrared spectral classification of the most extreme types of stars. Searches for variable objects and long–term monitoring at NIR wavelengths (e.g., Le Bertre 1992, 1993) should be done at larger scale especially in the Magellanic Clouds and in the inner Galaxy (Wood et al. 1998). With the development of large NIR arrays (up to 2k) the construction of the equivalent of Schmidt telescopes for the NIR range should be most advisable to probe large sky areas more deeply (up to K $\approx$ 20).

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