Part 6. AGB Stars as a Population of Various Galaxies

Andrejs Alksnis evocating the memory of Prof. Jurij Frantsman (1939–1998)

Asymptotic Giant Branch Stars
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AGB stars and galactic dynamics

H. Dejonghe and K. Van Caelenberg

Sterrenkundig Observatorium, Ghent University, Krijgslaan 281,
B-9000 Gent, Belgium

Abstract. AGB stars, seen as a stellar population, can be used to probe the dynamical state of galaxies. The relevant data are mostly positions and line-of-sight velocities, sometimes together with information on chemical composition and/or age. As of now, dynamical models have been made for OH/IR stars and Planetary Nebulae. Other candidates are C stars, S stars, and Miras. We review the methods used and the results obtained so far, for the Milky Way and for (relatively nearby) extragalactic stellar systems.

1. Introduction

It happens sometimes that data acquired for one purpose can be very useful for other purposes as well. A case in point are the AGB stars, which are studied in this volume mainly for their physical properties. If the data provide information on systemic velocities and if the set is sufficiently large and reasonably free of biases, it can be useful for dynamical analysis of our Galaxy or extragalactic systems. For obvious reasons, this contribution is kept as non-technical as possible.

Let us firstly recall the concept of stellar population: any class of stars that can be defined on the basis of physical characteristics of its members. These characteristics are such that they indicate a common origin, in place, in time, or both, given some a priori paradigm on the evolution of the stellar system to which they belong. The kinematics is not part of this definition; here it is seen rather as a property, which can be used to define subpopulations once a dynamical model is made, or to characterize the dynamical evolution.

The above definition is easily applied to, say, young stars, where the common origin is fairly obvious, and which do not yet have much of a history. However, by the time a star reaches the AGB phase, its very existence and evolution has been determined by the star formation rate, the initial mass function and the binary frequency, which all three depend on density, pressure, temperature and chemical properties of the interstellar medium. Moreover, our understanding of an AGB star depends on the theory of stellar evolution, of binary evolution and of the AGB phase itself in order to properly interpret the ages and chemical composition. Hence, there probably does not exist something like 'conservation of stellar population' in time, and AGB stars as a class are presumably the result of a mix of stellar populations. In short, it would be surprising to see that different classes of *old* AGB stars show different kinematics. The main thesis of this contribution indeed is that, at least for our Galaxy, these differences do not seem to exist.

This does not mean, of course, that there is little to be known from studying the dynamics of AGB stars. For instance, since the global gravitational potential is blind for all problems mentioned before, an AGB star is in principle as good a probe into the potential as any star. In fact, Planetary Nebulae (PNe) provide a very direct means of assessing the amount of dark matter in the halos of extragalactic systems. Because of space limitations, we will not discuss this very important topic any further.

2. AGB star roundup

In this section we will briefly review the properties of the most important classes of AGB stars, with special attention to the features that are relevant for a dynamical analysis. In general, their luminosity is a big advantage, because dynamical models need kinematical information over large volumes. Hence also infrared and radio astronomy occupy a privileged place. We will focus on AGB stars in those stellar systems that appear sufficiently relaxed so that a dynamical analysis seems possible.

2.1. OH/IR stars

These strong infrared emitters (several thousand $L_\odot$) shine right through the dusty Galactic Plane, a property which is helpful for a good spatial coverage. The characteristic double peak maser at 1612 MHz, caused by an expanding shell, is easily recognizable, and provides a simple way of measuring the systemic line-of-sight velocity. In addition, the velocity of the expanding circumstellar shell may indicate an age, in the (statistical) sense that larger expansion velocities are associated with younger stars. A metallicity effect may also be present however. The expansion velocity can thus be used to define OH/IR classes which may be identified with populations.

OH/IR stars have been detected in 2 ways. One method uses selection criteria on infrared colors (most often based on IRAS data). This method has been applied by Eder et al. (1988), Sivagnanam et al. (1989), te Lintel Hekkert et al. (1991a), with many more references, and David et al. (1993). The selected candidates are subsequently radio-checked for the 1612 MHz emission. The first dynamical models for these stars have been constructed by te Lintel Hekkert et al. (1991b). This early work established that dynamical models could reproduce the data, using a potential which did not differ in any substantial way from what was known at that time. There is also evidence for 2 distinct populations, based on differences in outflow velocity. See also Dejonghe (1993).

The alternative method simply rounds them up via a blind radio survey at 1612 MHz, which is particularly effective around the galactic plane and the Galactic Center (see te Lintel Hekkert et al. 1989, for a compilation of data before 1983). An early attempt to survey the Galactic Center was initiated by Habing et al. 1983), and has been substantially improved in a more limited region by Lindqvist *et al.* (1992a). Dynamical analysis can be found in Lindqvist *et al.* (1992b). The authors find evidence for a central mass concentration of the order of $10^7 M_\odot$ at 4 pc. Subsequent analysis by Sevenster et al. (1995) compares this sample with the te Lintel Hekkert et al. (1991b) data. The authors confirm the existence of 2 populations of OH/IR stars. The Lindqvist sample is a rather pure set of the younger population, while the te Lintel Hekkert et al. data consists of both populations. Further survey work includes seven fields in the galactic plane, surveyed by Blommaert et al. (1994). Sevenster et al. (1997a, b) have surveyed and published the strip $|b| \leq 3°$, $-45° \leq l \leq 10°$. Other data in other regions may be forthcoming.

A few caveats must be mentioned. (1) OH/IR stars are variable, and any survey is thus in principle a snapshot of an (unknown) fraction of the total population, which is obviously dependent on detector sensitivity. Monitoring of the Galactic Center region has been done by van Langevelde et al. (1993), and been used to obtain additional detections by Sjouwerman et al. (1998). (2) In some cases there is clearly maser emission at the right wavelength, but without the characteristic double peak. (3) OH/IR stars can be detected only in our Galaxy. Distances are in general unknown, and it is not clear how completeness varies as function of distance.

2.2. Planetary Nebulae

Their abundant radiation in emission, most notably in the [O III] line at 500.7 nm, good for about 15% of the radiative power, makes them real lighthouses. Detection of individual stars is possible, even at large distances (up to 20-30 Mpc), and analysis of the spectrum yields the determination of a radial velocity and abundances. The latter quantity can be used to identify different populations. For our purposes, we only consider the Planetary Nebulae (PNe) for which radial velocities are known.

Galactic PNe PNe are also strong infrared emitters, and occupy a fairly well defined place in infrared colour-colour diagrams (Pottash et al. 1988; Ratag et al. 1990). The catalog by Acker et al. (1992) is a critical compilation of all known measurements in the (vast) literature at that time. A complete compilation of radial velocities of galactic PNe is performed by Durand et al. (1998), with references therein. There are very important but unquantifiable selection biases present in these catalogs, since they originate in large part from literature searches. Add to this problem the galactic extinction in the plane (most of it is optical work), and it will be clear that these catalogs are unsuitable to yield star counts (see also later). Nevertheless, if the COBE 2μm map is substituted for the star counts, useful dynamical models can be made (Durand *et al.* 1996). These authors could not obtain a fit with two-integral models (see later), thus demonstrating the need for a global dependence on the third integral.

Extragalactic PNe The search for extragalactic PNe has now only begun in earnest. Most often candidates are found by blinking two images, one of them taken in a narrow band filter around [O III], the other in a sufficiently wide band that does not contain [O III]. Subsequent multifiber spectroscopy yields the radial velocities. This method has been fully exploited by Ciardullo, Jacoby, Hui, Ford and coworkers (see e.g. Hui & Ford 1993). Variants of this technique include selection on the basis of colour-colour diagrams (Theuns & Warren 1997). A quite different approach uses a Fabry-Perot instrument (e.g. Tremblay et al.

1995). A new and very promising technique searches with a dedicated instrument using the Counter Dispersed Imaging technique (Douglas et al. 1997). Very briefly, PNe will appear as shifted point sources through a (slitless) spectrograph. After rotation of the instrument by 180°, the PNe can be identified, and the line-of-sight systemic velocity follows after calibration with a foreground star.

2.3. C stars, S stars and Miras

We will consider these 3 classes together, not because there is an astrophysical reason to do so, but because the line-of-sight systemic velocity is obtained for all three of them in the same way: a spectrum is cross-correlated with a template. The spectrum evidently yields chemical information, which may be used to identify stellar populations.

C stars have been searched for in the Galaxy through objective prism surveys (Nassau & Velghe 1964; Aaronson et al. 1989, 1990), colour-colour or colour-magnitude diagrams (Green et al. 1994; Totten & Irwin 1998). S stars have been surveyed by means of Hα or near-IR surveys (Henize 1960; MacConnell 1982; Van Eck et al. 1998). The most extensive catalogue is that of Stephenson (1984). As far as the Miras are concerned, detection obviously is based on their variability, which makes them the longest period known AGB stars. The General Catalog of Variable Stars is the standard source for Galactic Miras. IRAS follow up has resulted in many Miras being found in the Galaxy as well (e.g. Whitelock 1994).

As all this work is optical, it is of course vulnerable to extinction effects. Template mismatch is always a worry with cross-correlation techniques, and the errors on the line-of-sight velocities are generally larger than those that can be obtained with emission line work.

3. Dynamical models

The basic question of stellar dynamics is: (1) how does one distribute stars on orbits, in order to reproduce the observations? (2) How does one interpret success or failure to do so?

The conceptually simplest way to go about this problem is to perform N-body simulations: stars are put on orbits, and these are integrated. It is a very general method, and the gravitational effects of gas, dark matter, etc... are easily incorporated (in principle). However, in order to start, one needs the initial conditions of the stars, and the gravitational potential, if stars are not the only players. All samples, except the Miras, have in common that the distances to individual stars are poorly, if at all, known. In most cases, proper motions are also absent. Hence it is clear that a dynamical analysis based on orbit reconstruction is a risky business, especially if the sample size is not large (a few hundreds). This problem can be alleviated by assuming a priori information on the nature of the orbits. This is hard to do in this case: e.g., it is a bit of a stretch to assume that an intermediate or old population moves on circular orbits.

The concept of an orbit therefore must be simplified in order to be useful. Since every sample is a snapshot in time, one intuitively sees that time-independent characteristics of the orbits, if these exist, are probably most useful (see also Dejonghe 1992, for a different approach). Such quantities, which remain constant along an orbit, are called integrals of the motion. For example, if the gravitational potential $V(\vec{r})$ is stationary, the energy $E = \frac{1}{2}\vec{v}^2 + V(\vec{r})$ is such a quantity. If the potential also has axial symmetry along the z-axis, it follows from general theory that the angular momentum component $L_z = (\vec{r} \times \vec{v})_z$ is also an integral. Numerical experiences show that most orbits in stationary potentials conserve also a third integral I_3 fairly well, be it possibly over more limited periods in time. A general theorem does not exist.

The basic question now becomes: (1) how do we obtain the distribution of the stars over these integrals, and what is the distribution function $F(E, L_z, I_3)$? (2) How does one interpret success or failure to do so?

The first question is more technical, especially its first part, and will not be discussed here. We refer the reader to te Lintel Hekkert et al. (1991b), or Dejonghe (1992), Dejonghe (1993), Sevenster et al. (1995) or Durand et al. (1996), and note that the method used in these papers does not depend on distance information to the individual stars.

There are 2 obvious aspects to the second question. (1) The quality of the fit depends on the adopted potential: a dynamical model allows a discussion on the total mass of the stellar system, and possibly its shape. (2) The form of the distribution function provides information on the dynamical state of the system: are there clumps in integral space that indicate different dynamical histories? Is the function $F(E, L_z)$ (i.e. two-integral) rather than $F(E, L_z, I_3)$? The former is believed to represent a population that is more mixed than the latter, which is an indication on age.

When the gravitational potential varies in time, the concept of integral of the motion loses its meaning, and one must try to assume special time dependences for the distribution function and work from there. A so-called mode analysis is such a method, but a discussion is beyond the scope of this contribution.

4. A comparison of a few galactic AGB samples

We will now check our hypothesis that the different AGB classes considered in Sect. 2 are unlikely to be very different dynamically, though differences probably exist between subclasses of one particular class (for OH/IR stars, see Habing 1993, te Lintel Hekkert *et al.* 1991b and Sevenster et al. 1995). This is not in contradiction with our conjecture here, because fine-tuning within a class may very well depend on age and metallicity.

Therefore, we compare the kinematics of 4 samples that we had available in electronic form: 885 mostly IRAS based OH/IR stars from the te Lintel Hekkert et al. (1991b) sample 'OH/IR(tL)', 507 OH/IR stars from the Sevenster et al. (1997a, b) survey 'OH/IR(S)', 867 PNe from the Strasbourg collaboration (Acker et al. 1992) 'PNe', and 478 carbon stars from the Aaronson et al. (1998, 1990) survey 'C' which covers 12 fields in the strips $|b| \leq 3°$, $-117° \leq l \leq -47°$ and $55° \leq l \leq 138°$.

Clearly not every sample is everywhere complete. We will use as our reference the COBE $2\,\mu$m data, which are generally believed to provide a good and reasonably extinction-free representation of the intermediate and old age

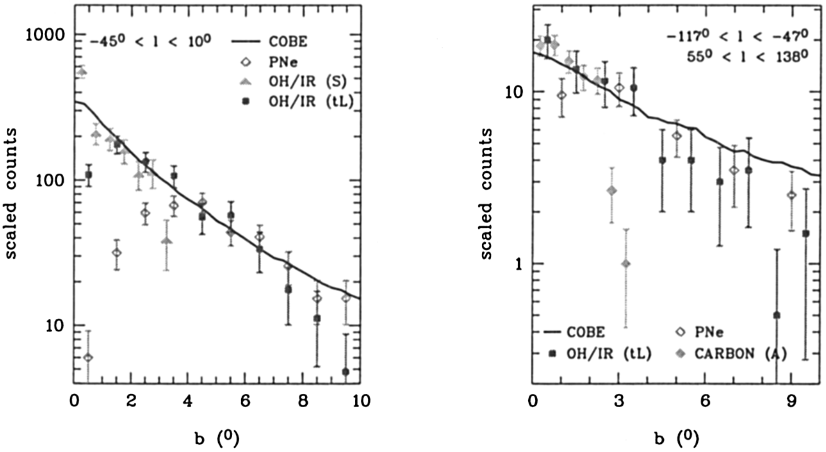

Figure 1. Star counts, summed over the indicated interval in galactic longitude, and scaled to the COBE counts.

population in the Galaxy. We will ignore asymmetries in galactic longitude l in the COBE data that are known to be present and generally believed to be due to the bar, because the relatively poor number statistics of the AGB samples do not allow detection of such an effect. Hence we will use a $2\,\mu$m map that is symmetrised in l and symmetrised in galactic latitude b, and apply the same symmetrisation to the 4 samples.

In Fig. 1 we compare the star counts, summed in longitude as indicated, as a function of $|b|$. The samples were scaled to coincide with each other and with the COBE counts as much as possible. We judge a sample complete if it follows the COBE counts. The results can be summarized in the following table.

	OH/IR(tL)	OH/IR(S)	PNe	C
$-45^\circ \leq l \leq 10^\circ$	$2^\circ \leq \lvert b\rvert \leq 6^\circ$	$\lvert b\rvert \leq 3^\circ$	$\lvert b\rvert \geq 4^\circ$	—
$-117^\circ \leq l \leq -47^\circ$ $55^\circ \leq l \leq 138^\circ$	$\lvert b\rvert \geq 2^\circ$	—	$\lvert b\rvert \geq 3^\circ$	$\lvert b\rvert \leq 2^\circ$

Table 1. Regions in the sky where the four samples follow the COBE $2\,\mu$m data. In all, about 1 000 stars qualify.

Having established where a comparison of the 4 samples makes sense, we now turn to the kinematics. As is clear from Fig. 2, one would be hard pressed to argue that any difference between samples might exist.

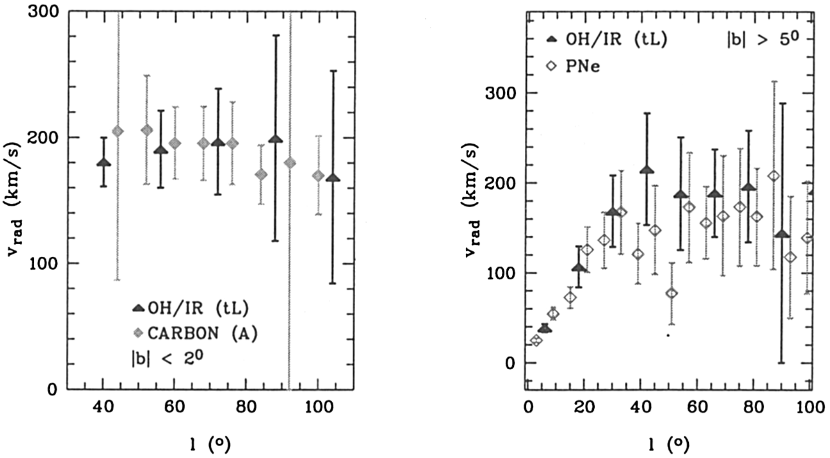

Figure 2. A comparison of line-of-sight velocities, summed over the indicated interval in galactic longitude, for different samples.

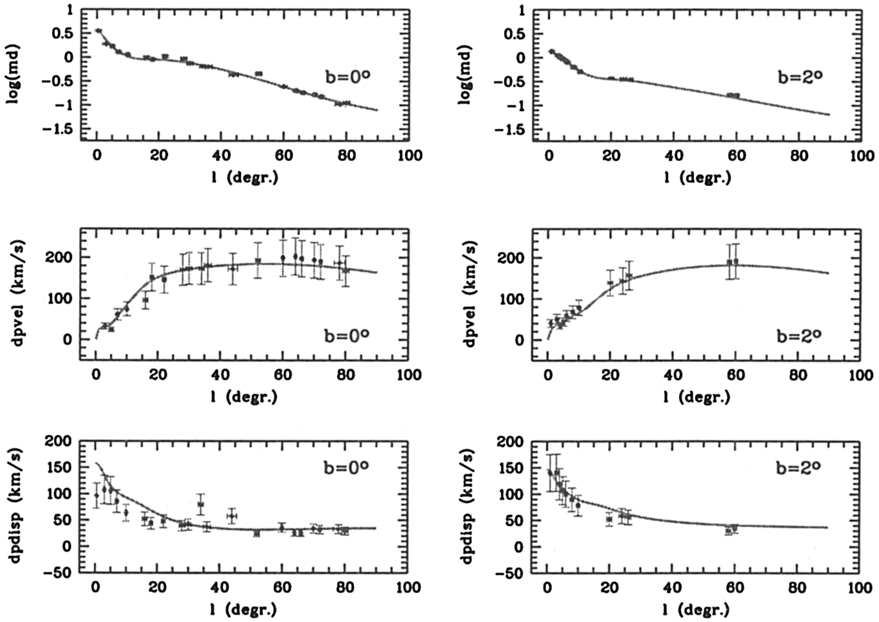

Figure 3. The COBE 2μm density (upper panels), the projected mean velocity (middle panels) and the projected velocity dispersions (lower panels) of the model (full curves), superimposed on the data.

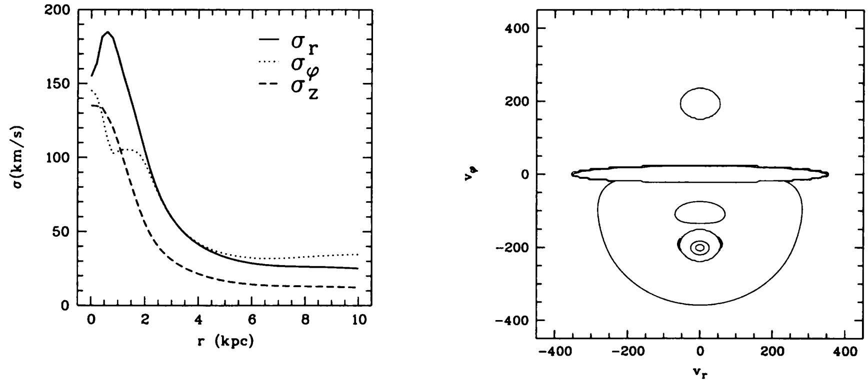

Figure 4. The intrinsic velocity dispersion as a function of galactocentric radius (left panel), and the velocity distribution in the Galactic Plane at the solar radius (right panel)

5. A dynamical model

Since we want to make genuine three-integral dynamical models, we assume a Galaxy potential that admits a third integral for all orbits: a so-called Stäckel potential. Batsleer & Dejonghe (1994) have constructed a large number of acceptable and simple potentials, of which we use the one with (in their notation) $a_D/c_D = 75$, $a_H/c_H = 1.01$ and $k = 0.07$. The distribution function is a sum of elementary and analytical functions, with coefficients determined by a Quadratic Programming technique. The method follows essentially the procedures used by Sevenster et al. (1995), except that the 3-integral components are of Abel type (Dejonghe & Laurent 1991). Fig. 3 compares data and model.

The construction of a dynamical model can be seen as a sophisticated deprojection. For example, the model has a mass density, that is the distribution of the mass in three dimensional space, while the original data only cover a range in l and b, with no distance information. By projecting the model back onto the sky, we get a density that is compatible with the observed one. More importantly however, the deprojected model is not a simple deprojection, but is supported by a distribution function: it can be realized by putting stars on orbits.

The left panel of Fig. 4 shows the velocity dispersion of our model in the r, φ and z directions (cylindrical coordinates) in the Galactic Plane. We see that the dispersion σ_z is smaller than σ_r, as could be expected. The curves for σ_φ and σ_r on the other hand, seem to indicate a dispersion in v_φ that is higher than that in the radial direction. This is of course not a very plausible result. However, the second plot of Fig. 4 represents the underlying distribution function in the (v_r, v_φ) plane, at $r = 8$ kpc, and makes clear that the velocities indeed do behave the way they are supposed to do. The velocity distribution clearly is more complex than can be inferred from the intrinsic velocity dispersions. In order to get the proper picture of the dynamical structure of the Galaxy, one needs to look at the underlying distribution function, since the dynamical structure is too complex to be 'summarized' in only a few numbers.

6. Conclusions

We argue that it is unlikely that large differences in the kinematics of different classes of old AGB stars exist in the Galaxy, and demonstrate that this is indeed true for OH/IR stars, PNe and C stars. We review the detection methods for these stars, with special attention to datasets with dynamical relevance. We produce, for the first time, a global dynamical model that incorporates different classes of AGB stars. We discuss the intrinsic velocity dispersions, and show that they may give misleading information on the dynamical structure, hence demonstrating the need to also consider the distribution function. Finally, it can safely be stated that upcoming large infrared surveys (such as DENIS and 2MASS) will turn up many more AGB stars, yielding large samples with well-understood biases.

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