Modelling the winds of AGB stars

An adventure in 1D and 3D radiative transfer

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1 Introduction

One of the later evolutionary stages of low- to intermediate-mass stars (with masses $\sim 0.8 - 8\ M_\odot$) is the asymptotic giant branch (AGB). Stars on the AGB have exhausted hydrogen and helium in their cores and are only fusing these elements in thin shells surrounding the cores, while the rest of the envelope has expanded massively to a size about 1 AU (Astronomical Unit, the average radius of the Earth's orbit around the Sun). The inherent instability of this system results in pulsations and mass loss. This extensive mass loss, which will often see the AGB stars reduced to less than half their original mass, impacts the stellar surroundings and eventually the whole galaxy. The amount of mass lost will determine how much gas and dust is available to form the next generation of stars, and the distribution of white dwarf stars left behind from the cores of the AGB stars. Therefore determining the mass-loss rates of AGB stars is an important question that people have been grappling with for many years. The measured mass-loss rates range from $\sim 10^{-8}$ to $10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$.

When gas is thrown far enough away from the central star, to where conditions are sufficiently cool, it is able to condense into molecules and dust grains. When stellar photons hit these dust grains, they impart some of their momentum, pushing the dust grains away from the star. The dust grains then collide with gas particles and transfer some of their momentum, pushing the gas outwards as well. A schematic of this dust-driven wind mechanism is shown in Fig 1. For further reading about dust-driven winds, see Höfner & Olofsson (2018) and references therein. For more information on the topic of AGB stars, see the text book by Habing & Olofsson (2003).

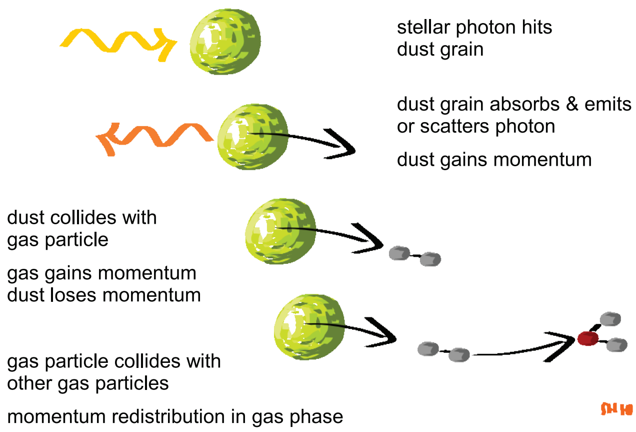

Figure 1: Microphysics of dust-driven winds: Dust grains acquire momentum from stellar photons and transfer it to the surrounding gas via collisions. Figure taken from Höfner (2011).

The gas and dust ejected by the star form an expanding circumstellar envelope, which can be observed using many different techniques. An excellent way to study the kinematics of the envelope, and derive its mass, is to observe the emission of the most abundant molecules. Unfortunately the most abundant molecule by far, H_2, is difficult to excite and hence to observe. Luckily the next most abundant molecule, CO, forms readily and is very stable due to the triple bond between the carbon and oxygen atoms. AGB star chemistry is divided into three types depending on its ratio between carbon and oxygen molecules in its atmosphere: oxygen-rich (C/O < 1), S-type (C/O $\sim$1), and carbon-rich (C/O > 1). Most of the less abundant of the two elements will be locked up in CO, leaving an overall oxygen-rich, mixed, or carbon-rich chemistry in the envelope, and a large abundance of CO. CO has a range of low-frequency rotational transitions that are easily excited in cool gas ($\lesssim$100 K). Its abundance relative to H_2 is also fairly constant across different types of AGB star ($\sim 10^{-4}$) so converting from a CO abundance to an assumed envelope mass requires only a few assumptions. However, to derive the CO abundance we need radiative transfer modeling.

In this assignment you will be modelling the CO emission around two different AGB stars: WX PSc and π^1 Gru. In WX Psc, the circumstellar envelope can be assumed to be spherically symmetric and we can therefore use a 1D purely radial model. In π^1 Gru, the envelope is clearly not spherically symmetric and we must model its full 3D geometry (albeit in a simplified way). We will use a radiative transfer code called Magritte, developed here at KU Leuven by Dr.

Frederik De Ceuster (for details, see De Ceuster et al. 2020), which is available at `https://github.com/Magritte-code/Magritte`. Radiative transfer requires solving the radiative transfer equation iteratively, as the radiation field and CO (or other molecule) level populations affect each other (see the lecture notes on radiative transfer in environments outside of local thermodynamic equilibrium). This problem can be approached in different ways: Magritte computes the radiation field by tracing rays through the model and solving the radiative transfer equation along those rays, with a fixed set of rays originating from each point.

The following sections will describe the 1D and 3D modeling you will undertake, and some information about the sources. The modeling will be done in python notebooks, available at `https://github.com/FredDeCeuster/StellarAtmospheres_assignments`

2 WX PSc: 1D modeling of a spherical wind

2.1 Source information

WX Psc is a very late type oxygen-rich AGB star, which means it has been on the AGB a long time. It has therefore already lost a lot of mass, and its mass-loss rate is likely to be high as this property tends to increase as the star traverses the AGB. It is also quite bright, with a luminosity of over 10^4 $L_\odot$, and has a high wind expansion velocity of 19.8 km/s, as measured from the width of the CO lines. This is around the maximum velocity we expect for a spherical wind. For this star we have spectra of three different CO transitions, shown in Figure 2, which we will try to fit with a single model. As can be seen from the spectra, the lines have relatively smooth parabolic shapes, indicative of a spherically symmetric mass loss (or, rather, any deviations from spherical symmetry should be small).

2.2 The 1D model

As the circumstellar envelope of WX Psc seems to be largely spherically symmetric you will model it with a 1D model, where the only changes are in the radial direction. We will also assume a single mass-loss rate and expansion velocity, so the gas density will simply scale with the volume, and a simple power-law function for the temperature:

$$T = T_{in} \left(\frac{r_{in}}{r}\right)^{\epsilon} \tag{1}$$

where T_{in} is the temperature at the inner edge of the circumstellar envelope, r_{in}. As the envelope is assumed to start where it is cool enough for dust to condense, this is assumed to be 1000 K, the condensation temperature for silicate dust. The exponent ϵ is generally found to be between 0.5 and 1 for AGB stars.

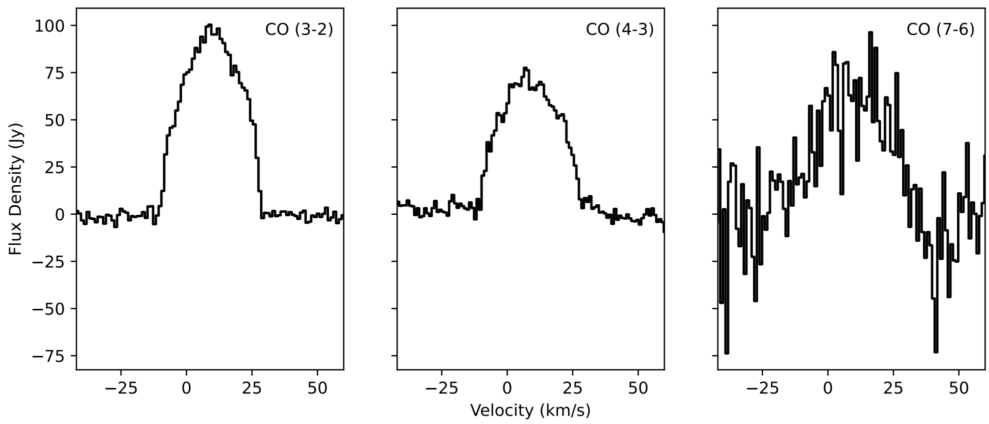

Figure 2: Spectra of WX PSc, in three different transitions of CO, taken with the APEX telescope.

2.3 Your task

Vary the mass-loss rate and exponent of the temperature profile (ϵ), and compare the model output to the WX Psc spectra to find the best fit model. This will be done by minimizing the reduced-χ^2 value, a common measure of the goodness-of-fit, which uses the following formula

$$\chi^2 = \frac{1}{N-p} \sum_{i=1}^{N} \frac{(F_{\mathrm{mod},i} - F_{\mathrm{obs},i})^2}{\sigma_i^2} \tag{2}$$

where N is the total number of data points (i.e. wavelength bins in the spectrum), p is the number of parameters being varied, F is the model or observed flux at the wavelength corresponding to the observation, and σ is the uncertainty on the observed flux. The best-fitting model is the one with the smallest χ^2 value, although you should always also perform a visual inspection of the model and data plots. Compare your results with those found by De Beck et al. (2010) for WX Psc (see their Table 7 and text).

3 π^1 Gru: 3D modeling of a complex wind

3.1 Source information

π^1 Gru is an S-type AGB star, meaning it has a C/O ratio around 1. This also implies it is a relatively late type AGB star, as all AGB stars start off oxygen-rich and, depending on initial mass, dredge up more carbon to the stellar surface over time. The circumstellar envelope will have a mixed chemistry, rather than predominantly oxygen- or carbon-rich, and CO is still by far the most abundant molecule after H_2. π^1 Gru has a known main sequence companion star at a separation of 2.7 arcseconds ($\simeq$400 AU), but its wind's observed deviations from spherical symmetry suggest there is also a second, closer companion (within $\sim$10 AU) shaping the wind.

To study this star we have interferometric data taken with the Atacama Large Millimeter/submillimeter Array (ALMA) of the CO (3-2) line. Radio interferometry provides a data cube, which is a series of images of the emission at each frequency. This means we can both extract a spectrum over a spatial region of the data cube – as seen in Figure 3, where the spectrum has been extracted from a large circular aperture covering all the emission – and image the emission at different velocities (=frequencies) across the molecular line – this is called a channel map, as seen in Figures 4 and 5 (found after the references).

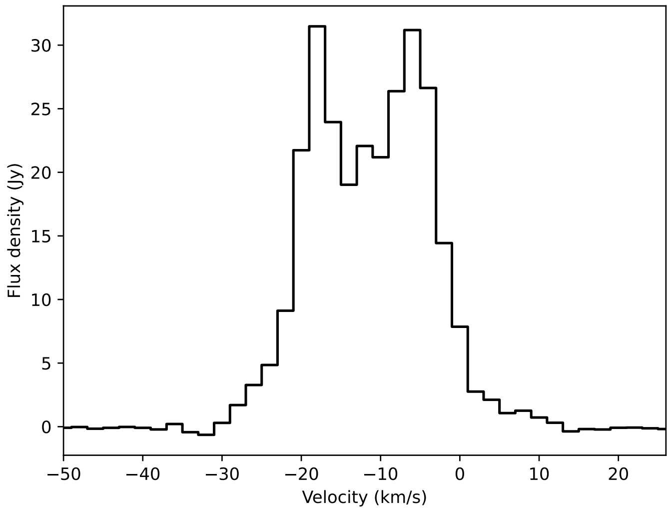

Figure 3: Spectrum of the CO (3-2) line in π^1 Gru

The CO spectrum of π^1 Gru (Figure 3) is clearly not a simple parabolic shape, but instead shows multiple components. The broad line wings show that we have emission out to very large velocities, $\sim$45 km/s from the central velocity, which is an indication of a fast bipolar outflow. This is supported by the channel map in Figure 5 which shows the emission at these large velocities is a round feature to the north at the bluest (most negative) velocites, and to the south at the reddest (most positive) velocities. These have been interpreted as the walls outlining the end of a bipolar jet. In the central $\sim$30 km/s we see more complex features (Figure 4), which are also primarily in the north on the blue side and in the south on the red side. Remember that the emission we see at a given velocity is only the component in our line-of-sight, so to find the geometry and inclination angle of the system we will need modeling.

3.2 The 3D model

Previous studies have shown this emission is consistent with a torus or donut shape, where the gas has been confined to the equatorial plane by interaction with a companion star. The bipolar outflow is then perpendicular to this torus (i.e. appearing to flow out of the hole on either side of the donut). We have defined a simplified system consisting of an equatorial torus with a constant velocity and a fast bipolar outflow perpendicular to the torus with a velocity increasing linearly from 11 to 89 km/s.

3.3 Your task

Vary the inclination of the system and velocity of the torus to find the best-fit model. To do this you will both compare your model output to the CO (3-2) spectrum, again minimizing the χ^2 value as above, and visually compare with the channel maps. These two methods may not lead to the same best-fit model, and it's up to you to decide how to weigh them and choose one best-fit model. Compare your results to the results of similar modeling by Chiu et al. (2006) and Doan et al. (2017)

4 Write a report

Now that you have found the best fit models in both 1D and 3D, write a small report of maximum 5 pages (additional figures are allowed in an appendix) describing the scientific context and your methods and results, including how you chose the best-fit model and how your results compare to previous results. You will probably not have been able to find a model that fits the data exactly, as there are many factors that cannot be taken into account in this simple exercise or indeed in the Magritte code. Discuss how well a simple model can constrain the parameters of these stellar winds, and what modifications might be made to this exercise and to Magritte to improve modelling outcomes.

This report should be handed in before the exam in June, and will account for 2 (out of the 20) exam points.

References

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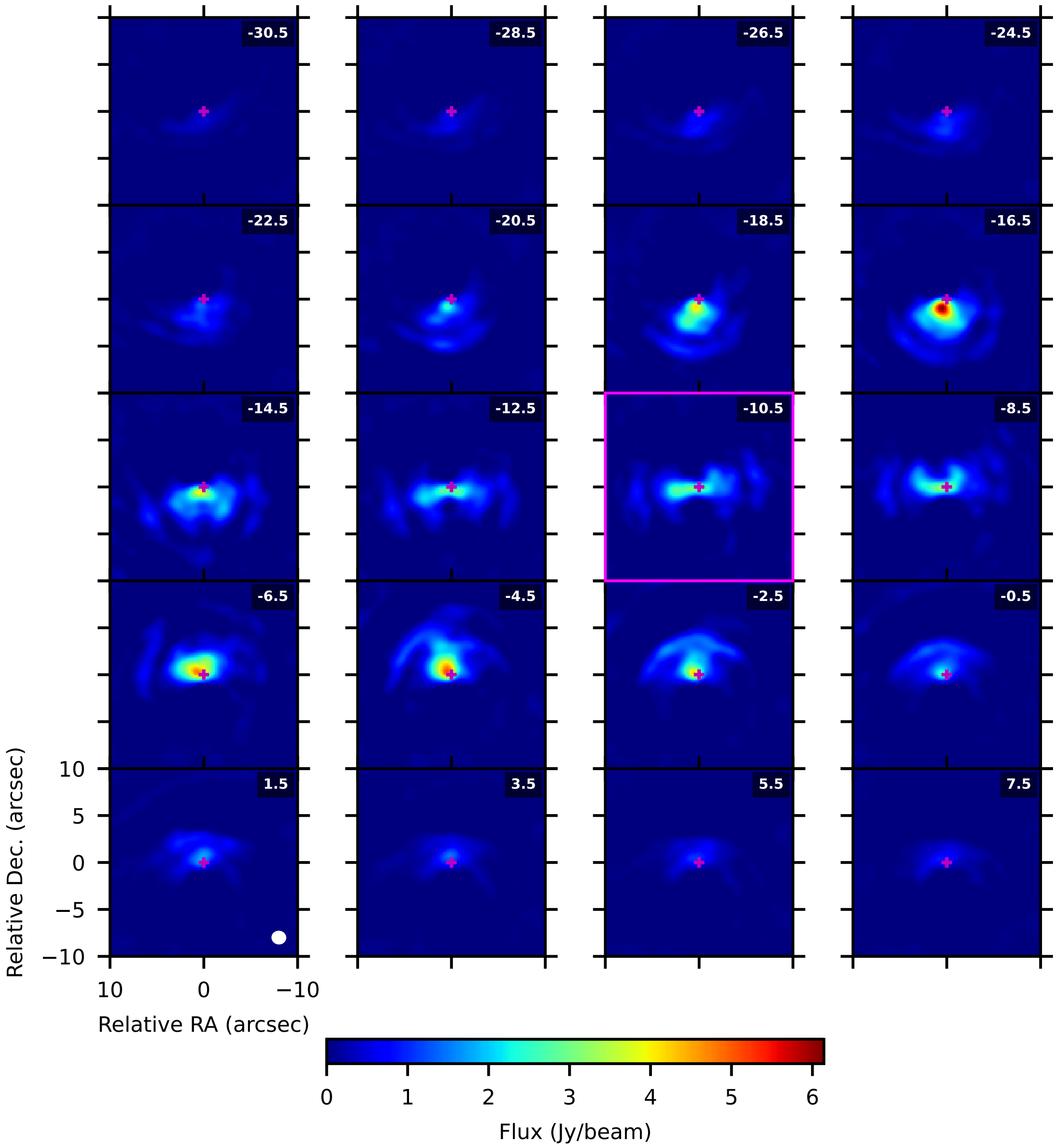

Figure 4: Channel map of the CO (3-2) line in π^1 Gru, as observed with ALMA. The image closest to the central velocity is highlighted in pink.

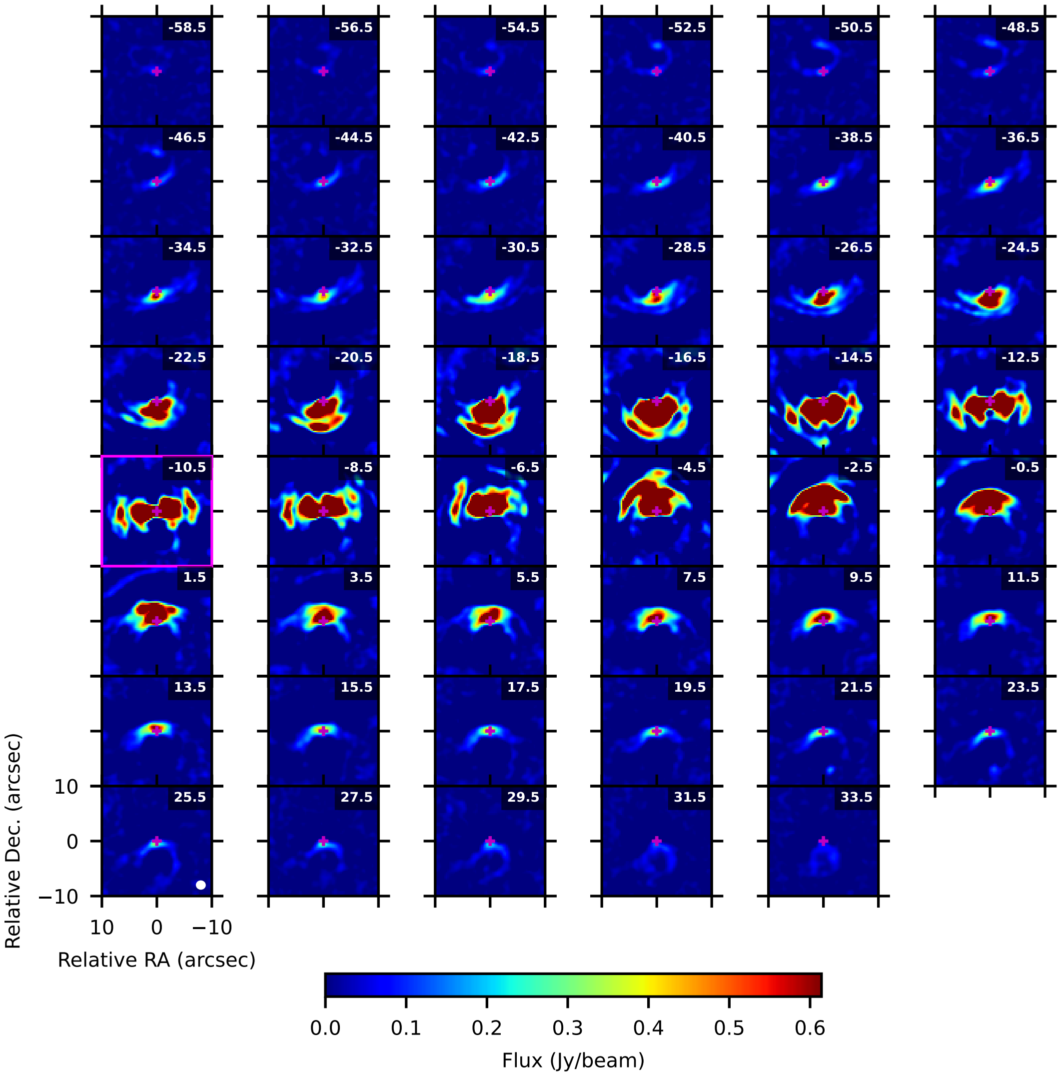

Figure 5: Extended map of the CO (3-2) line in π^1 Gru, with a color scale to emphasise the faint features at extreme velocities.