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Time Variability of Molecular Line Emission in IRC +10216

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Abstract. We present the results of monitoring the molecular emission of the C-rich AGB star IRC+10216 over 3 years with the Herschel Space Observatory. Observations of rotational transitions of various vibrational levels of CO, ^{13}CO, CS, CCH, H_2O, SiO, SiS, SiC_2, HCN and HNC have been collected with the HIFI, PACS and SPIRE instruments over multiple epochs. The intensity monitoring shows strong and periodic variations of most of the observed molecules, often with differential behavior depending on the transition level (larger variation at higher J), and generally enhanced modulations in the vibrational modes of some of these molecules (e.g. HCN). These results show that the effect of IR pumping through the different vibrational levels on the emergent line profiles of a given transition can be really significant. This implies that the IR radiation field of the circumstellar envelope and its time variation has to be taken into account in any radiative transfer model in order to derive accurately the physico-chemical structure of the envelope.

1. Introduction

IRC+10216 (CW Leo), like all Mira-type stars, shows significant amplitude modulation in the visible and the IR (~ 2 mag in the I band over a period of 635 days, Alksnis 1989). However, variation in the rotational levels of many of the molecular species present in the envelope (excited mainly through collisions) was shown to be negligible, especially in the outer shell which is probed at millimeter wavelengths (Cernicharo, Guélin & Kahane 2000). Observations of thermal lines with the Herschel Space Observatory, however, revealed significant intensity variations on a 6 month time interval that could not be explained by instrumental effects. It is noteworthy, however, that some other species such as SiC_2 (Cernicharo et al. 2010) did not show any noticeable variation.

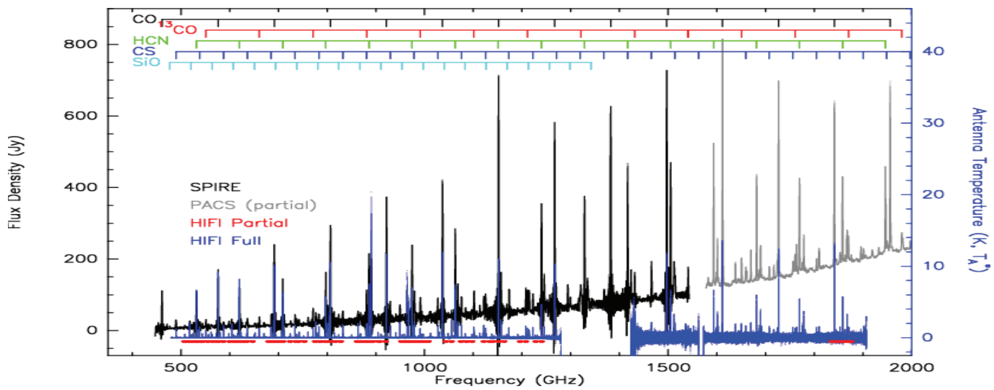

Figure 1. Example of a set of data collected at a single epoch. The HIFI data in blue correspond to the full spectral scan (Cernicharo et al. 2010), while the red portion corresponds to the part of the spectrum regularly monitored. The PACS data are only shown in the range overlapping with HIFI, but they extend down to 70 μm. The frequencies of typical line ladders are indicated in the upper part of the plot.

This motivated the monitoring of nearly a hundred of spectral line transitions for the remainder of the *Herschel* mission. We present here the data obtained in this context and highlight some of the first results.

2. Data-set Acquisition and Data Analysis

The data-set consists of multi-epoch observations of a large portion of the sub-mm and far-infrared spectrum of IRC+10216 obtained using the three spectrometers on-board *Herschel*. Full range spectroscopy was obtained with both PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010), stemming both from our monitoring program and from regular instrumental calibration campaigns. For HIFI (de Graauw et al. 2010), dedicated tuning observations were performed to monitor $\sim$80 thermal lines spread over the instrument's operational range. Additional measurement points were obtained from two other studies of this object (Cernicharo et al. 2010, Agúndez et al. 2011).

Figure 1 illustrates the typical set of data obtained for a given epoch. For each epoch and spectral range, the source continuum was estimated and isolated from the spectral line emission (for HIFI no significant continuum emission was detected, so the overall baseline level was simply subtracted). For each line and epoch, integrated line intensities were computed. For PACS and SPIRE, the lines are spectrally unresolved so Gaussian or Cardinal sine functions were respectively fitted at the expected line positions. For HIFI, spectrally resolved profiles cannot be fitted with a simple function due to the complex velocity structure. Line fluxes were integrated within predefined velocity windows. The collection of line fluxes at various epochs provides a light curve that is then fitted with a simple sine function where amplitude, phase, period and average flux are considered free parameters. This approach is similar to the analysis of light curves in the visible and near infrared (NIR) (e.g. Menten et al. 2012). Figure 2 shows the typical outcome of this fitting exercise over a collection of HCN transitions measured by PACS. On average, the fitted periods are in line with those derived from the NIR, albeit sometimes with large error bars. This parameter will however not be discussed further in this paper.

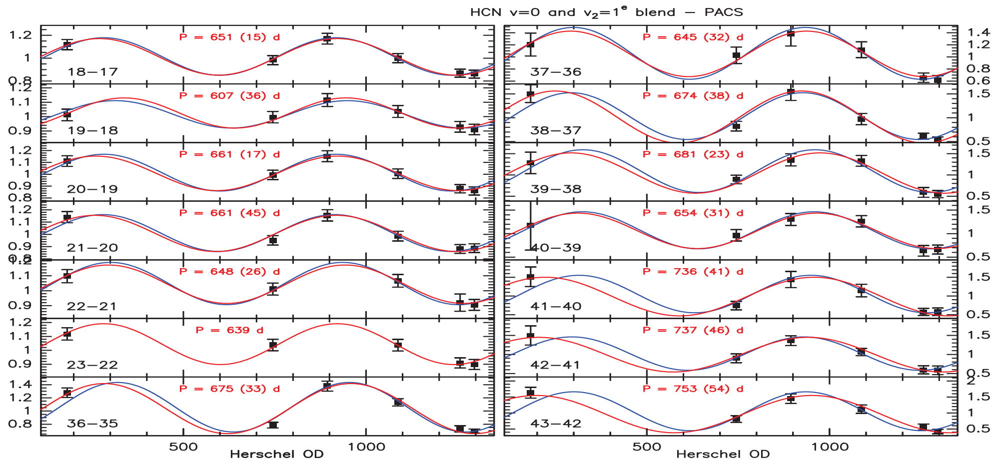

Figure 2. Sample light curves of the integrated line intensity of the HCN ladder in the PACS spectral range. Intensities are normalised to the mean. A sine wave fit with a fixed period of 635 days is shown in blue, while the full free-parameter fit is shown in red, together with the fitted period in days in each box. The time axis is given on a scale of *Herschel* Observational Day OD (OD 1 is 14 May 2009).

3. Continuum Variability

Using the continuum SED isolated from the line emission, it is possible to create light curves at any wavelength and fit them with sine functions. Figure 3 shows an example of the fitted modulation at two wavelengths falling in the respective PACS and SPIRE ranges. The modulation fitted at 250 μm is consistent with that derived by Groenewegen et al. (2012) using the SPIRE photometer. While the fitted periods are in good agreement with those inferred from the photometer, and do not vary too much with wavelength, the amplitude of the fitted modulation tends to increase with decreasing wavelength, ranging typically from 25 % at 600 μm to more than 50 % at 80 μm.

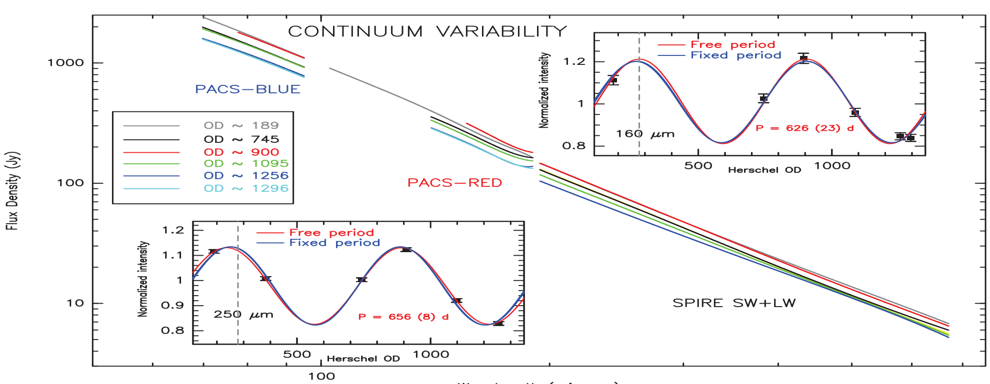

Figure 3. PACS and SPIRE continuum SED extracted at various epochs. Fits to the continuum light curves at two wavelengths are given in the two insets. The vertical dashed lines in the insets show the time of maximum light fitted by Groenewegen et al. (2012) on SPIRE photometer data at 250 μm.

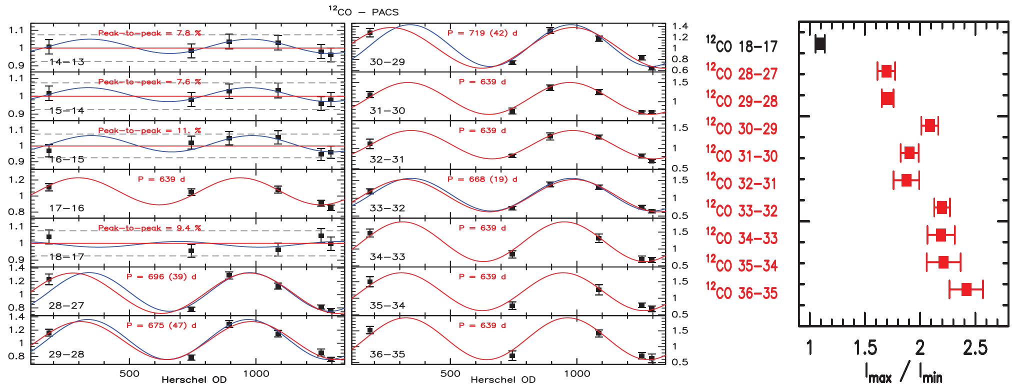

Figure 4. *Left*: Same as Fig. 2 for the CO ladder. Horizontal dashed lines indicate the range of flux calibration uncertainty. The J=17-16 transition is blended with an HCN ν_1=1 line, leading to the large modulation. *Right*: Ratio between the maximum and minimum measured line flux as a function of rotational level in the higher range of PACS. The J=18-17 transition, interpreted to be unmodulated, is shown in black.

4. CO Line Variability

The analysis of the CO lines is probably the most widely-used tool to measure the main properties of circumstellar envelopes around AGB stars, and in particular to derive mass-loss rates. With the advent of suitable detector and telescope technology, transitions of higher excited lines have been progressively added to such analyses, allowing us to probe the emission in more internal layers of the envelope and to constrain e.g. the gas temperature profile more precisely (e.g. de Beck et al. 2012). Such studies, however, usually rely on a plethora of data collected over various telescopes and epochs, implicitly assuming that the CO line emission is not varying with time. Our data-set suggests that this assumption is fine typically up to rotational levels in the range J = 13 to 18. In this range however, the modulation is within or only marginally above the typical instrument calibration errors so it is difficult to draw firm conclusions (see e.g. the left panels of Figure 4). When one gets to rotational levels in the higher PACS frequency range (J = 28 and above), line flux increases in excess of a factor of 2 are observed, and they tend to scale together with the upper energy level (see right panel of Fig. 4).

5. Infrared Pumping

HCN lines in various vibrational states have been detected for several rotational transitions. The high spectral resolution of HIFI allows us to separately analyse lines from ν=0 (ground-state), ν_1=1 and ν_3=1 (stretching modes with rotational ground-states lying at 3 and 4.8 μm respectively), and ν_2=1^e, ν_2=1^f and ν_2=2 (bending mode comprising an l-type doubling and the first overtone, with rotational ground-states lying at 14 and 7 μm respectively). For PACS and SPIRE data, line blends occur between respective transitions of the ν=0 and ν_2=1^e modes, and the ν_2=1^f and ν_2=2 modes. Figures 2 and 5 illustrate the light curves of several of these transitions for PACS and HIFI data, together with their sine fit (see caption for further details). The right panel of Fig. 5 shows the evolution of the maximum measured flux ratio at different rotational levels,

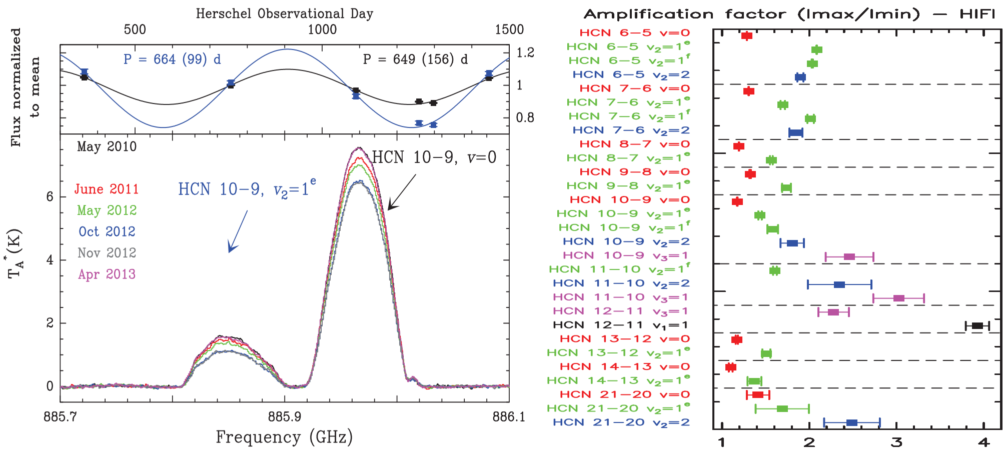

Figure 5. *Left*: Example of HCN lines detected with HIFI. The lower panel shows the respective spectra observed at different epochs. The upper inset shows the light curves of the integrated intensities normalised to their mean, and their fit with a sine function and the fitted period. *Right*: Maximum over minimum line flux ratio for various vibrational modes and rotational levels for all HCN lines detected with HIFI.

and for the various vibrational modes. A clear trend is observed, whereby the amplitude of the modulation increases progressively from the ground-state to the bending modes, then to the two stretching modes, in line with the progressively increasing energy levels associated with the respective ro-vibrational transitions. Considering the high energy levels involved, collisional pumping is unlikely, so that radiative pumping must be invoked. Because the corresponding wavelengths are probably very close to those at which the stellar flux experiences the largest amplitude modulation, the effect we observe here should be a direct consequence of infrared pumping of the ro-vibrational transitions.

A similar effect is seen in the emission of the C_2H molecule. This exhibits the largest amplitude modulation of the whole sample (line flux increase larger than a factor of 5 for the N=7-6 and N=8-7 transitions). De Beck et al. (2012) have already pointed out the importance of including the first three vibrational modes to reproduce the observed line intensities in the HIFI range. Once again, the radiative pumping involved occurs at wavelengths (3–27 μm) where the stellar flux experiences large variation. On top of that, the first stretching mode of C_2H is coupled to the first electronically excited state ($A^2\Pi$), lying at 2.5 μm. All this shows that the infrared radiation field of a circumstellar envelope, and its time variation, has to be taken into account in radiative transfer models, in order to derive an accurate physico-chemical structure of the shell.

References

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Discussion

Whitelock: A comment about fitting the cosines to the variations. These stars do not repeat their light cycles with any precession – so this is not a useful procedure.

Teyssier: It is correct that photometric light curves do not consist of only a periodic component (see e.g. Alksnis et al. 1989). It is, however, common practice to approximate the stellar flux modulation with a simple cosine to derive pulsation characteristics such as period or amplitude (see e.g. Menten et al. 2012). In our study in particular we are interested in how the modulation amplitude varies with the excitation, and the cosine approximation is good enough for that purpose.

Franz Kerschbaum, Thomas Lebzelter and David Teyssier enjoying the boat trip on the Danube.