Molecular line survey with Herschel/HIF of the Rotten Egg?



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Abstract

We have performed a ~479-1244 GHz spectral line survey with Herschel/HIFI of the well studied O-rich envelope OH 231.8+4.2 (a.k.a. The Rotten Egg nebula after the high abundance of H₂S in its envelope). This object displays fast (>400 km/s), bipolar outflows and a molecular richness unparalleled amongst O-rich AGB and post-AGB stars and is considered ``The Rosetta-stone" for studying non-equilibrium, shock-induced chemical processes in O-rich environments.

The main result of this work, is a full census of farIR lines in OH231 is provided together with flux measurements, line profiles, and other line parameters. The line flux is dominated by CO, H₂O, and S-bearing species (and their main isotopologues). The line profiles vary with species and upper level energy, which has enabled to investigate their presence in the different outflow components, the temperature stratification, and the velocity field in the envelope. Preliminary analysis of the data, by means of the population diagram technique, has provided rotational temperatures and column densities for these molecules (including isotopologues). We have also used complementary data at low-frequency from our ~79-350GHz spectral survey with EMIR at the IRAM-30m telescope (e.g. Velilla et al. 2010).

12CO

5.762 10⁵

a= 11.17K*km/s Eu=116.2K; co

Introduction

The interstellar medium is enriched primarily by matter ejected from ~1-8Msun evolved stars via the heavy mass loss that they experience as Asymptotic Giant Branch (AGB) stars. Dust-driven stellar winds create dense, cool circumstellar envelopes (CSEs) of molecular gas and dust that are among the most complex chemical environments in space. The chemistry in the stellar atmosphere is dominated by the high dissociation energy of the CO molecule. This has the effect that essentially all carbon is bound in CO for stars with a C/O < 1 (i.e. M-type AGB stars) with the remaining O forming oxygen-based molecules such as OH, SiO, and H₂O.The opposite is true for carbon (C/O>1) stars. Important changes in the composition of the CSE occur when the central object starts its evolution beyond the AGB phase towards the Planetary Nebula (PN) stage. In the very short (~1000yr) AGB-to-PN transition period (so-called pre-PN) phase), some physical process accelerates (up to >100-1000kms) and imposes bipolarity upon the stellar wind. The passage of shocks caused by the hydrodynamical nteraction between the fast, collimated post-AGB wind and the slower AGB CSE is expected to produce a variety of radicals and ions that activate a vast collection of non-equilibrium chemical reactions. Moreover, as the star gradually evolves along the AGB-to-PN evolutionary track to earlier spectral types and the surrounding envelope takes apart from the star, becoming progressively more and more diluted, the chemistry is further affected by the penetration of both stellar and insterstellar photons through the detached CSE.

Date	Band	Freq.range	η_{eff}	HPBW	Obs. time	rms†
		(GHz)	(%)	(")	(h)	(mK)
2011-10-27	1a	479.6-561.5	75.6	40.9	3.2	5
2012-05-02	1b	554.6-636.6	75.4	35.7	2.9	5
2011-10-26	2a	626.1-726.0	75.2	31.5	4.2	8
2011-10-28	2b	714.1-802.0	75.0	28.1	2.9	12
2012-04-20	3a	799.2-860.1	74.7	25.6	2.4	14
2012-04-25	3b	858.2-961.1	74.4	23.4	4.2	14
2012 04 26	45	040.2 1061.1	74.1	21.2	3.6	30

OH231.8+4.2 (The Rotten Egg)

• Chemically richest O-rich CSE amongst AGB and post-AGB stars • O-rich $\sim 3M_{\odot}$ AGB star (M6-9 III) + [A0 main seq. companion] • d ~1500pc, L~10,000 L_{\odot} Mloss~le-4 M_{\odot} yr⁻¹

•~50"-long, shocked bipolar nebula + narrow, dusty waist (Fig. 1) • Molecular envelope ($~1M_{\odot}$):

- Central core (torus+disk): V_{exp}~7-20km/s
- Axial lobes (hollow): V_{exp} ~400 km/s

• Large, axial velocity gradient, ~6.5 km/s arcsec⁻¹. Axis inclination ~36^o

It is believed that the bipolar flow is the result of a sudden interaction between fast (<400km/s) jet-like ejections and the slow AGB CSE, which took place ~ 1000 yr ago in a relatively short time, <100 yr. Molecules are expected to be initially destroyed by such high-speed shocks. At present, the shocked material has cooled down sufficiently to allow molecule reformation. Given the moderate densities in the fast, bipolar flow ($\sim 10^3 - 10^5 \text{ cm} - 3$), the abundances of the secondeneration molecules in the post-shocked gas have probably remained "frozen".



Figure 2. HSO/HIFI spectrum of OH231 (9-channel smooth-average).

Results

The full SSB spectrum of OH231.8 is shown in Figure 2 (above).

2012-04-25	Ja	1100.2-1244.1	04.0	10.1	0.1	45
2012/04/25	52	1108 2 1244 1	64.0	18 1	6.1	45
2012-05-04	4b	1046.7-1122.1	73.7	19.6	2.3	30
2012 01 20	144	2 12 12 1001.1	/ 1.1		2.0	20

Table 1. Summary of HSO/HIFI observations. F_{eff}~96%. Rms $(\Delta v = 4.5 \text{ MHz}).$

Observations and data reduction

We have used the Herschel/HIFI in its spectral scan mode to perform a line survey (bands 1a-5a) of the well known, O-rich CSE OH231.8. Table 1 gives a log of the Herschel/HIFI observations We used the WBS, which provides a frequency resolution of $\Delta v=1.1$ Mhz ($\Delta v \sim 0.26-0.68$ km s-1) over 4 GHz of instantaneous spectral coverage. Both horizontal (H) and vertical (V) polarizations were simultaneously obtained. Observations were performed in the Dual Beam Switching (DBS) mode with a ' chop throw and with a redundancy of 4 for low frequency bands (1a-3b) and a redundancy of 3 for the high frequency pands (4a-5a). We have observed one single position towards e center of OH 231.8 (J2000 coordinates RA=7h 42m 16s.830; $\delta = -14^{\circ} 42' 52' \cdot 10$, **Fig. 1**). It is from these central regions where the bulk of the molecular emission arises. Raw Herschel/HIFI data have been reprocessed from level-0 to level-2 running the hifiPipeline task of HIPE1 (versions 9.0-11.0). Afterwards, level-2 spectra have been saved to FITS format and then imported by CLASS where standard data reduction routines have been applied, including DSB-to-SSB deconvolution.

5.51 10⁵ 5.509 10⁵

Molecules detected in OH231: CO, SiO, OH, H₂O, NH₃, NS, HCO⁺, SO, SO₂, H₂S, OCS, HCN, HNC, CN, NO, HC₃N, CS, H₂CO, HNCO, HNCS, SiS, N₂H⁺, SO⁺, and a number of isotopologues (bearing ¹³C, ³³S, ³⁴S, ¹⁷O, ¹⁸O, ²⁹Si, ³⁰Si, and ¹⁵N atoms). This includes literature data and new detections from our ~79-350GHz survey with EMIR at the IRAM 30m MRT (Velilla et al. 2010).



Figure 1. Left) ¹²CO emission

map of OH231.8. The two circles represent the largest and smallest HPBW of these observations. Right) Position-velocity diagram along the axis of the bipolar outflow. Area = 2.85K*km/s Eu=111.1K; 13co 6.612 10⁵ 6.611 10⁵ 6.61 10⁵ 6.609 10⁵



Molecular abundances

First-order, beam-averaged rotation temperatures and column densities for the different molecules observed have been obtained using the population diagram technique (Fig. 5). In some of these diagrams we have also included data from our low-frequency (79-350GHz) survey with EMIR/IRAM-30m. These diagrams point to different envelope components with different temperatures.

 \checkmark ~ 600 lines detected over ~765GHz (density=0.8I/GHz) \checkmark 70% of the transitions are condifiently identified (JPL, CDMS, and Cernicharo's private catalogue) \rightarrow Table 2 ✓ Spectrum dominated by CO, H₂O, S-bearing molecules ✓ Molecules detected with HSO/HIFI: Table 3 \checkmark Most lines are v=0 pure rotational transitions \checkmark Vibrationally excited (v=1) lines from H₂O, SiO, SO, HC₃N?...

Line profiles of selected transitions are shown in Fig. 3:

- Intense narrow core (FWHM~20-35 km/s). Bulk of the emission arises in the central core (13 in Fig. 1).
- Weak broad wings arising in the outflow regions (mainly from the base of the outflow, I4 at V_{lsr} ~50-70 km/s).

Line core of some species is double-peaked (at ~28 and 40 km/ s) \rightarrow equatorial disk expanding at ~7km/s.

The line width increases as the upper level energy (E_{μ}) drecreases (i.e. outwards) – see Fig. 4. Also, there is a trend of decreasing V_{lsr} for increasing E_{ll} .





CO, ¹³CO, SO, CS, SiO, HCN, COLD ~10-40K HNC, HCO+, NH_3 , H_2CO WARM ~70-100 K SO, CS?, SiO, SiS, H_2S , H_2CO . CS. SiO (maser

Fractional abundances f(X) are estimated relative to that of ¹³CO adopting f(¹³CO)=5e-5 as estimated by Morris et al. (1987). Values are given in **Table 3**



Final Remarks and Future. At the

completion of this work (which includes non-LTE radiative transfer and chemical modeling), we will obtain a detailed picture of the chemical composition and molecular excitation across the different nebular regions in OH231, from the densest, warmest (>100K) layers close to the central star to the more tenuous, cooler (≈10K) parts. Since the chemistry in OH231.8 is profoundly affected by shocks rather than UV stellar photodissociation processes (given its low stellar temperatures) we should be able to identify the best molecular shock-chemistry tracers, specially those resulting from fast (~400 km/s), dissociative shocks.

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	¹² CO	5×10	$\gtrsim 7.7(2.0) \times 10^{17}$	14 (3)	1.5×10^{-4}		
0		5×10	$4.4(1.0) \times 10^{17}$	43 (3)	1.5×10		
	¹³ CO	4×8	$3.4(0.2) \times 10^{17}$	11(1)	5×10^{-5}		
	CO	4×8	$1.6(0.3) \times 10^{17}$	45 (2)	5×10		
	$C^{18}O$	4×8	$1.4(0.2) \times 10^{16}$	31 (2)	2×10^{-6}		
	SO	4×8	$2.2(0.3) \times 10^{16}$	29 (1)	3×10^{-6}		
	502	4×8	$1.3(0.7) \times 10^{15}$	330 (140)			
	SO	4×8	$1.3(0.3) \times 10^{16}$	27 (2)	2×10^{-6}		
	50	4×8	$1.2(0.4) \times 10^{15}$	61 (5)	2/10		
	NH ₃	4×8	$\gtrsim 7.0(4.0) \times 10^{14}$	21 (4)	$\gtrsim 3 \times 10^{-7}$		
	CS	4×8	$8.8(0.3) \times 10^{14}$	21 (2)	1.0×10^{-7}		
	CD	4×8	$3.3(1.2) \times 10^{13}$	190 (50)			
	HCN	4×8	$7.8(0.50) \times 10^{14}$	10 (2)	$>2\times10^{-8}$		
	nen	4×8	$1.4(0.04) \times 10^{14}$	32 (2)	~2~10		
	HCO^+	4×8	$3.0(0.5) \times 10^{14}$	14(1)	5×10^{-8}		
	HNC	4×8	$2.6(1.7) \times 10^{14}$	24 (5)	4×10^{-8}		
	SiO	4×8	$2.6(0.1) \times 10^{14}$	14 (2)	4×10^{-8}		
	510	4×8	$3.6(0.7) \times 10^{13}$	82 (8)			
	SiS	4×8	$9.7(3.0) \times 10^{13}$	60 (11)	3×10^{-8}		
	010	4×8	$6.2(1.6) \times 10^{13}$	260 (50)			
	HaCO	4×8	$1.9(0.05) \times 10^{14}$	12 (2)	2.5×10^{-8}		
	11200	4×8	$7.2(1.70) \times 10^{13}$	48 (6)	2.37(10		
	$^{13}CS^{\dagger}$	4×8	$1.5(0.07) \times 10^{14}$	27 (8)	2.5×10^{-8}		
	CD	4×8	$3.1(0.2) \times 10^{13}$	244 (14)			
	*		1.0.00 1.0.15		7		
	H_2O^*	4×8	$>1.2(0.3)\times10^{13}$	230 (70)	>2×10 ⁻⁷		
	$H_2^{10}O^{+}$	4×8	$7.0(1.8) \times 10^{13}$	130 (30)	$>1.3\times10^{-8}$		
	$H_2^{1/O}$	4×8	$5.1(2.1) \times 10^{15}$	100 (35)	≥1.0×10 ⁻ °		
	H_2S^*	4×8	$\gtrsim 1.8(0.7) \times 10^{13}$	140 (40)	≥3×10 ⁻⁷		
	$H_2^{34}S^*$	4× 8	$4.6(1.7) \times 10^{14}$	120 (40)	8.0×10^{-8}		
	$H_2^{33}S^*$	4×8	$2.2(0.9) \times 10^{14}$	75 (30)	4.0×10^{-8}		
	NS	4×8	$9.8(4.0) \times 10^{13}$	170 (50)	2×10^{-8}		
	* Uncertain due to optical depth and/or non-LTE effects						
	+ Upportain due te lour S/N dete						
	+ Uncertain due to low S/IN data						

Table 3. Results from the population diagram analysis

References: Morris et al. 87; Sánchez Contreras et al. 1997, 2000, 2001, 2004; Alcolea et al. 2002; Bujarrabal et al. 2004; Desmurs et al. 2008; Velilla et al. 2010.