MESS
Mass loss of Evolved StarS

Early spectroscopic results

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Scientific Goals:

To obtain complete spectral coverage from 55-685um at resolving powers ranging up R=3500 (PACS) and R=1200 (SPIRE), in order to:

(a) Characterise the atomic and molecular chemistry in the outflows from O-rich and C-rich evolved stars.

(b) Determine the dominant coolants, the temperature structures and the mass loss rates of the outflows.

(c) Characterise dust spectral features, where found, as well as dust continuum emissivity laws, for sources that have known chemistries (e.g. known C/O ratios)
SPIRE FTS Spectra of MESS Evolved Objects

SPIRE SAG 6 members and consultants:

CRL 2688 C-rich PPN
CRL 618 C-rich PPN
NGC 7027 C-rich PN
IRC+10216 C-rich AGB
VY CMa O-rich supergiant
Smith et al., 2001
Smith et al., 2001
Five luminous evolved MESS targets were observed with the SPIRE FTS during SDP:

VY CMa: O-rich self-obscured M supergiant (Teff~2800 K)

IRC+10216 (CW Leo): self-obscured carbon star

AFGL 2688: C-rich bipolar post-AGB object (A/F-type star)

AFGL 618: C-rich bipolar post-AGB object (early B-type star)

NGC 7027: C-rich planetary nebula (150,000 K central star)
SPIRE SLW
SPIRE SSW

Flux levels agree to within 25%
Unapodized FTS spectrum

(see Naylor & Tahic 2007)

1.5 Apodized FTS spectrum
(see Naylor & Tahic 2007)
VY CMa

Royer et al. (P2.30)
Matsuura et al. (P2.32)

wavelength [μm]

HCN
SO₂
H₂¹⁸O
SiO

H₂O
¹³CO
¹²CO

Wavenumber [cm⁻¹]

1199.170 GHz

1349.066 GHz
VY CMa: species detected in the SPIRE FTS range:

(~300 emission lines from 14.6 – 52 cm\(^{-1}\); 192-685\(\mu\)m)

\(\text{o-H}_2\text{O}\)
\(\text{p-H}_2\text{O}\)
\(\text{^{18}H}_2\text{O}\)
\(\text{^{12}CO}\)
\(\text{^{13}CO}\)
\(\text{SiO}\)
\(\text{HCN}\)
\(\text{CN}\)
\(\text{NH}_3\)
VY CMa: LTE fit with 6 molecules
NLTE water line models for VY CMa. 3 codes:

SMMOL; GASTRoNOoM; 1DART

See Matsuura et al. (P2.32)
Carbon-rich sources

- IRC+10216
- AFGL 2688
- NGC 7027
- AFGL 618

233um

- CO 11-10
- CO 12-11
- HCN
- AFGL 2688
- AFGL 618
- NGC 7027
- IRC+10216

200um

- CO 13-12
- HCN

Wavenumber (cm$^{-1}$)
IRC+10 216: SLW and SSW overlap region
First detection of HCl in an evolved star outflow (Cernicharo et al. 2010, A&A; P1.34)

\[ \text{HCl/H}_2 \sim 5 \times 10^{-8} \]

Model fits use \(^{35}\text{Cl}/^{37}\text{Cl} = 3.1\) (from other CW Leo chlorides)
Species detected so far in the FTS spectrum of IRC+10216 (~250 emission lines):

\[ ^{12}\text{CO}, \ ^{13}\text{CO}, \ ^{18}\text{O} \]

HCN, H\(^{13}\)CN

SiS

SiO

o-H\(_2\)O, p-H\(_2\)O

NH\(_3\)

CCH

CS

HCl
Continuum-subtracted FTS spectra of AFGL 2688, AFGL 618 and NGC 7027 (Wesson et al., 2010, A&A)
Cernicharo et al. (1997) detected the J=2-1, 3-2 and 4-3 lines of CH$^+$ in the LWS spectrum of NGC 7027.

CH$^+$ is created in PDRs by

\[ \text{C}^+ + \text{H}_2 \rightarrow \text{CH}^+ + \text{H} \]

(e.g. Yan et al. 1999; needs \( T \sim 500-1000 \) K);

and by

\[ \text{C}^+ + \text{H}_2^* \rightarrow \text{CH}^+ + \text{H} \]

(Agundez et al. 2010)
AFGL 618: Orange curves: LVG models of Herpin & Cernicharo (2000) for $^{12}\text{C}/^{13}\text{C} = 21$

NGC 7027: fairly low rotational $T_x$'s derived from CO and CH$^+$

P2.35
MESS
Mass loss of Evolved StarS

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PACS spectroscopy of evolved stars (55-210 μm)

- 27 AGB/RSG
- 26 Post-AGB/PN
- 2 WR/LBV

GOALS:
- study mass-loss history, chemical processes, dust formation, ...
NGC 7027
C-rich PN
$T_{\text{eff}} \approx 140000 \text{K}$

- IRC+10216
- C-rich AGB
- VY CMa
- O-rich supergiant

Smith et al., 2001

PACS
1. PACS and SPIRE Spectroscopy of the Red Supergiant VY CMa
   Royer et al.

2. Detection of Anhydrous Hydrochloric Acid, HCl, in IRC+10216 with the
   Herschel SPIRE and PACS spectrometers
   Cernicharo et al.

3. Silicon in the dust formation zone of IRC+10216
   Decin et al.

PACS MESS ESLAB posters

P 1.34 Hydrides in IRC+10216. Detection of HCl with PACS and SPIRE
   Cernicharo et al.

P 2.30 PACS and SPIRE Spectroscopy of the Red Supergiant VY CMa
   Royer et al.

P 2.32 Unraveling the Chemical Complexity of VY CMa with the PACS and
   SPIRE Spectrometers
   Matsuura et al.
PACS observations

PACS footprint and S/C boresight positions

Dec

RA


-25°45'30”

-25°46'00”

-25°46'15”

-25°46'20”

-25°46'25”

-25°46'30”

-25°45'40”

-25°45'45”

-25°45'50”

-25°45'55”

-25°46'10”

-25°46'05”

-25°46'15”

-25°46'20”

-25°46'25”

-25°46'30”

B on  A on  Source
PACS observations

VY CMa

Flux [arb.]

Wavelength [μm]
Spectral movie VY CMa
# First spectroscopic results

## Molecular inventory

<table>
<thead>
<tr>
<th>VY CMa</th>
<th>IRC+10216</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL: ~250 unblended</td>
<td>+ unidentified lines</td>
</tr>
</tbody>
</table>

- $^{12}\text{CO}$, $^{13}\text{CO}$, C$^{17}$O, C$^{18}$O
- NH$_3$
- OH
- SiO
- HCN
- CN
- CS
- SO
- SiS
- H$_3$O$^+$?
- [C II]
- [O I]

$\hat{\text{o-}}\text{H}_2\text{O}$ \} 2/3 of all lines

$\hat{\text{p-}}\text{H}_2\text{O}$
First modeling results of VY CMa
Royer et al. (2010)
First modeling results of VY CMa
Royer et al. (2010)

Line peak intensity of o-H$_2$O (7$_{1,6}$-6$_{2,5}$)

Black bullet: central target
White dashed contour: diffraction limited beam size at 66 μm (5”)
Black dashed contour: instrumental PSF at half Maximum
Outer white contour: 50% of max. H$_2$O intensity

Smith et al. 2001
First modeling results of VY CMa
Royer et al. (2010)
First modeling results of VY CMa
Royer et al. (2010)

1D-non-LTE modeling

\[ T_\ast = 2800 \text{K} \]
\[ M_\ast = 15 \, M_{\odot} \]
\[ L_\ast = 3 \times 10^5 \, L_{\odot} \]
\[ D = 1140 \, \text{pc} \]
\[ [\text{CO}/H_2] = 3 \times 10^{-4} \]
First modeling results of VY CMa
Royer et al. (2010)

1D-non-LTE modeling

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\[ M_\ast = 15 \, M_{\text{sun}} \]
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\[ D = 1140 \, \text{pc} \]
\[ [\text{CO}/\text{H}_2] = 3 \cdot 10^{-4} \]

\[ \dot{M} = 1.5 \cdot 10^{-4} \, M_{\text{sun}} / \text{yr} \]
\[ ^{12}\text{C}/^{13}\text{C} = 60 \]
\[ [\text{SiO}/\text{H}_2] = 4.5 \cdot 10^{-5} \]
\[ [\text{H}_2\text{O}/\text{H}_2] \approx 3 \cdot 10^{-4} \]
\[ [\text{HCN}/\text{H}_2] = 4.5 \cdot 10^{-6} \]
First modeling results of VY CMa
Royer et al. (2010)

1D-non-LTE modeling

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\[ M_* = 15 \, M_{\text{sun}} \]
\[ L_* = 3 \cdot 10^5 \, L_{\text{sun}} \]
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\[ [\text{HCN}/\text{H}_2] = 4.5 \cdot 10^{-6} \]

ortho-to-para ratio 1.27:1
non-equilibrium chemistry
First spectroscopic results

Molecular inventory

**VY CMa**

TOTAL: ~250 unblended

\[
\begin{align*}
\text{o-H}_2\text{O} \\
\text{p-H}_2\text{O} \\
\text{^{12}CO, ^13CO, C^{17}O, C^{18}O} \\
\text{NH}_3 \\
\text{OH} \\
\text{SiO} \\
\text{HCN} \\
\text{CN} \\
\text{CS} \\
\text{SO} \\
\text{SiS} \\
\text{H_3O^+?} \\
\text{[C II]} \\
\text{[O I]} \quad + \text{unidentified lines}
\end{align*}
\]

2/3 of all lines

**IRC+10216**

TOTAL: ~250 unblended

\[
\begin{align*}
\text{H^{12}CN} \\
\text{H^{13}CN} \\
\text{^{12}CO, ^13CO, C^{18}O} \\
\text{o-H}_2\text{O} \\
\text{p-H}_2\text{O} \\
\text{NH}_3 \\
\text{SiS} \\
\text{SiO} \\
\text{CS} \\
\text{C}_3 \\
\text{C}_2\text{H} \\
\text{HCl} \\
\end{align*}
\]

1/2 of all lines
# First spectroscopic results

## Molecular inventory

### VY CMa

- \( p-H_2O \)
- \( o-H_2O \)
- \( ^{12}CO, ^{13}CO, ^{17}O, ^{18}O \)
- \( NH_3 \)
- \( OH \)
- \( SiO \)
- \( HCN \)
- \( CN \)
- \( CS \)
- \( SO \)
- \( SiS \)
- \( H_3O^+? \)
- \([C \ II]\)
- \([O \ I]\) + unidentified lines

**TOTAL:** ~250 unblended lines

\[ \begin{aligned}
\{ & \text{2/3 of all lines} \\
\{ & \text{1/2 of all lines} \\
\end{aligned} \]

### IRC+10216

- \( ^{12}CO, ^{13}CO, ^{18}O \)
- \( H^{12}CN \)
- \( H^{13}CN \)
- \( o-H_2O \)
- \( p-H_2O \)
- \( NH_3 \)
- \( SiS \)
- \( SiO \)
- \( CS \)
- \( C_3 \)
- \( C_2H \)
- \( HCl \)

**TOTAL:** ~250 unblended lines

+ unidentified lines
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

High J lines of SiO and SiS: trace dust formation zone

SiO : $J=11-10$ to $J=90-89$ ($E_{up} = 8432$ K)
SiS: $J=26-25$ to $J = 124-123$ ($E_{up} = 6678$ K)
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

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SiS: \( J=26-25 \) to \( J=124-123 \) (\( E_{\text{up}} = 6678 \) K)

Role in AGB dust formation?
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

1D non-LTE modeling

$T_\ast = 2050\,\text{K}$

$M_\ast = 1\,M_{\odot}$

$L_\ast = 8.1 \times 10^3\,L_{\odot}$

$D = 150\,\text{pc}$

$[\text{CO}/\text{H}_2] = 1 \times 10^{-3}$

From $^{12}\text{CO}$ and $^{13}\text{CO}$ lines:

$J=3$ (at 31 K) to $J=47$ (at 5853 K)

determine thermophysical structure in envelope
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

1D non-LTE modeling

\[ T_\star = 2050 \text{K} \]
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\[ [\text{CO}/H_2] = 1 \cdot 10^{-3} \]

From $^{12}$CO and $^{13}$CO lines:

- J=3 (at 31 K) to J=47 (at 5853 K)
- determine thermophysical structure in envelope

\[ \dot{M} = 1 \times 10^{-5} \ M_{\text{sun}}/\text{yr} \]
\[ ^{12}\text{CO}/^{13}\text{CO}=30 \]
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

Constatnt fractional abundance in the envelope

$$\left[ \frac{\text{SiO}}{\text{H}_2} \right] = 1 \times 10^{-7}$$
$$\left[ \frac{\text{SiS}}{\text{H}_2} \right] = 4 \times 10^{-6}$$
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

\[
\frac{[\text{SiO}/H_2]}{[\text{H}_2]} = 1 \times 10^{-7}
\]

Schoier et al. (2006): from SiO J=2-1 to J=5-4 + interferometric map of SiO J=5-4:

- \( R < 3R_* \): \( \frac{[\text{SiO}/H_2]}{[\text{H}_2]} = 3 \times 10^{-8} \) \quad \text{TE-value}
- \( 3 < R < 8R_* \): \( \frac{[\text{SiO}/H_2]}{[\text{H}_2]} = 1.5 \times 10^{-6} \) \quad \text{Grain surfaces act as catalyst and/or pulsationally induced non-TE chemistry}
- \( R > 8R_* \): \( \frac{[\text{SiO}/H_2]}{[\text{H}_2]} = 1.7 \times 10^{-7} \) \quad \text{Freeze out onto dust-grains}
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS \textbf{CONSTANT} fractional abundance in the envelope

\[
[\text{SiO}/H_2] = 1 \times 10^{-7}
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Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

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Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

\[ [\text{SiO}/\text{H}_2] = 1 \times 10^{-7} \]

R<8R*: [SiO/H2]=3 x 10^{-7}
R>8R*: [SiO/H2]=1 x 10^{-7}

0.2-3 x 10^{-7}

At maximum 30% takes part in dust formation
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

\[[\text{SiO}/\text{H}_2] = 1 \times 10^{-7}\]

- \(R<8R_*: [\text{SiO}/\text{H}_2]=3 \times 10^{-7}\)
- \(R>8R_*: [\text{SiO}/\text{H}_2]=1 \times 10^{-7}\)

\(0.2-3 \times 10^{-7}\)

* lowest SiO J=11-10
* low S/N high J-lines
* velocity field unknown → HIFI
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

\[ \text{[SiS/H}_2\text{]} = 4 \times 10^{-6} \quad \rightarrow \quad \text{At maximum 50\% takes part in dust formation} \]
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS constant fractional abundance in the envelope

\[
\frac{[\text{SiS}/\text{H}_2]}{\text{H}_2} = 4 \times 10^{-6}
\]

TE chemistry: \[
\frac{[\text{SiS}/\text{H}_2]}{\text{H}_2} = 1.5 \times 10^{-5}
\]
non-TE chemistry: \[
\frac{[\text{SiS}/\text{H}_2]}{\text{H}_2} = 3.4 \times 10^{-5}
\]

(Willacy & Cherchneff, 1998)

Formation of SiS

\begin{align*}
S + H_2 & \rightarrow HS + H \\
S + C_2H_2 & \rightarrow C_2H + HS \\
HS + Si & \rightarrow SiS + H
\end{align*}

Activation energy barriers: occur in hot `fast chemistry' zone of excursions induced by fast shocks

SiS + S + M \rightarrow SiS + M

Slow shock strengths
Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS - CONSTANT fractional abundance in the envelope

\[
\frac{[\text{SiS}/H_2]}{[\text{H}_2]} = 4 \times 10^{-6}
\]

TE chemistry: \(\frac{[\text{SiS}/H_2]}{[\text{H}_2]} = 1.5 \times 10^{-5}\)  
non-TE chemistry: \(\frac{[\text{SiS}/H_2]}{[\text{H}_2]} = 3.4 \times 10^{-5}\)  
(Willacy & Cherchneff, 1998)

Formation of SiS

\[
\begin{align*}
\text{S} + \text{H}_2 & \rightarrow \text{HS} + \text{H} \\
\text{S} + \text{C}_2\text{H}_2 & \rightarrow \text{C}_2\text{H} + \text{HS} \quad \star \\
\text{HS} + \text{Si} & \rightarrow \text{SiS} + \text{H} \quad \star \\
\text{SiS} + \text{S} + \text{M} & \rightarrow \text{SiS} + \text{M} \quad \star
\end{align*}
\]

Activation energy barriers: 
occur in hot `fast chemistry' zone of 
excursions induced by fast shocks

Slow shock strengths

\* = estimated rates
Detection of
* $^{12}$CO
* $^{13}$CO
* OH
* CH
* CH$^+$
* [O I]
* [O III]
* [C II]
* [N II]
* ....

* HD(0,0) R(0) @112.07 μm: NOT detected
* o-H$_2$O $2_{2,1}-1_{1,0}$ and $3_{2,1}-2_{1,2}$ suggested by LWS not detected with PACS
* H$_2$O tentatively detected o-H$_2$O $2_{1,2}-1_{0,1}$, $2_{2,1}-2_{1,2}$, $3_{0,3}-2_{1,2}$, and $1_{1,0}-1_{0,1}$

PLANS:
PACS + SPIRE + UV, optical and near-IR data: will be analysed with Cloudy
Conclusions

* PACS and SPIRE spectroscopic data: wealth of molecular line diagnostics: trace mass-loss history, chemical processes, excitation mechanisms, temperature structure, dust-gas coupling, ...
* only few molecules analyzed so far; already 3 articles published, few in prep.
* dust features → requires accurate RSRF
* combine with HIFI, ground-based data, interferometric maps
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* PACS and SPIRE spectroscopic data:
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* only few molecules analyzed so far; already 3 articles published, few in prep.
* dust features → requires accurate RSRF
* combine with HIFI, ground-based data, interferometric maps

Questions?

Spectral movie VY CMa
Spectral movie IRC+10216
Spectral movie NGC7027