Dynamics in atmospheres and outflows of evolved stars

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Quick intro

- Evolved stars in this talk
  = Post-Main-Sequence Giants
- $< 8 \, M_{\text{sun}}$
  AGB: asymptotic giant branch stars
- $>8 \, M_{\text{sun}}$
  RSG: red supergiant stars
- Cool surface $\sim 3000K$
- Luminous $\sim 100 - 100,000 \, L_{\text{sun}}$
- Mass loss $\sim 10^{-8} - 10^{-3} \, M_{\text{sun}}/\text{yr}$
Evolution and appearance on AGB strongly affected by range of dynamical processes

- large-scale convective flows
  >> transport of newly formed chemical elements to the surface
- stellar pulsations
  >> trigger shock waves in extended stellar atmosphere
- dust grain formation in upper atmosphere
  >> acceleration through scattering/absorption and collisions with gas
- massive outflows of gas and dust

These lead to
- enrichment of ISM
- evolution from giant to white dwarf
Dynamics of AGB stars

Observations of asymmetries and inhomogeneities
- short-lived & small-scale: photosphere and dust-forming layers
- long-lived & large-scale: circumstellar envelope

High-angular resolution observations give information on e.g. dust condensation
- location
- chemical composition
- size

“These are essential constraints for building realistic models of wind acceleration and developing a predictive theory of mass loss for AGB stars, which is a crucial ingredient of stellar and galactic chemical evolution models.”
Observations: large scales

Large scales = circumstellar envelope (CSE)
>> spherical
  • entire outflow
  • shells

Castro Carrizo et al. (2010)
CO (J=2-1), PdBI
IK Tau, normal mass loss

Olofsson et al. (2000)
CO (J=1-0), PdBI
TT Cyg, detached shell
Observations: large scales

Large scales = circumstellar envelope (CSE) 
>> spherical
  • entire outflow
  • shells

De Beck & Olofsson (2018)  
APEX spectral survey at 0.8-1.9 mm  
R Dor, normal mass loss
  • main, smooth, spherical component  
  • up to 4 extra components in the outflow  
    • one at velocities >> wind expansion velocity  
    • shells / rings / spiral / ... ?
Observations: large scales

Large scales = circumstellar envelope (CSE)

>> spherical
  • entire outflow
  • shells

>> not so spherical
  • binary interaction

Maercker et al. (2012, 2014, 2016)
R Scl, detached shell source
CO($J=3-2$), ALMA
Dust-scattered stellar light, PolCor

- previously unknown binary companion
  ~60 AU separation

- from spiral windings:
  information on changes in velocity and mass loss
  on evolutionary timescales

- Dust and gas dynamics comparable?
Observations: large scales

Large scales = circumstellar envelope (CSE)

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  • entire outflow
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Maercker et al. (2012, 2014, 2016)
R ScI, detached shell source
CO($J=3-2$), ALMA
Dust-scattered stellar light, PolCor

- previously unknown binary companion
  ~60 AU separation

- from spiral windings:
  information on changes in velocity and mass loss
  on evolutionary timescales

- Dust and gas dynamics comparable?
Observations: large scales

Large scales = circumstellar envelope (CSE)

>>> spherical
  • entire outflow
  • shells

>>> not so spherical
  • binary interaction
  • disk

Ramstedt et al. (2014)
Mira, 0.5" (~45 AU) binary separation
CO(J=3-2), ALMA, “bubble” in the AGB wind

Kervella et al. (2014, 2015, 2016)
L2 Pup
ALMA, VLT (NACO/SPHERE), edge-on disk
Observations: small scales

- Small scales
  - upper atmospheric layers (warm molecular layer)
  i.e. before wind acceleration

Khouri et al. (2016)
CO(\(\nu=1, J=3-2\)), ALMA

- inverse P-Cygni profiles indicate infall motion

- multiple epochs reflect changes of the upper atmosphere
  - temperature
  - density
  - motion
Observations: small scales

- Small scales
  - upper atmospheric layers
    i.e. before wind acceleration
  - dust formation region

Khoury et al. (2016), SPHERE/ZIMPOL, R Dor

- **Top**
  variable morphology in continuum
  = changing opacity of TiO in extended atmosphere

- **Bottom**
  polarised light from ~annular region around central star.
  - density profile steeper than constant- \( \nu \) wind
  - upper limit for the \( d/g \sim 2 \times 10^{-4} \) at \( 5.0 \) R\( \star \),
    consistent with minimum required by wind-driving models
Observations: small scales

- Small scales
  - upper atmospheric layers i.e. before wind acceleration
  - dust formation region
  - surface imaging

$\pi^1$ Gruis, VLTI/PIONIER
surface granulation due to convection

Vlemmings et al. (2017, *Nature Astro.*),
W Hya, ALMA
heating of the upper atmosphere due to shocks chromosphere?
Conclusions

**Mass loss** dominates appearance and evolution on AGB
>> critical to have predictive description as input for models of
  - stellar evolution
  - galactic chemical evolution
>> strongly dependent on variety of dynamical processes

**Observations** show
  - asymmetries and inhomogeneities
    - on large spatial scales & long timescales
    - on small spatial scales & short timescales
  - dust location, size, composition
  - surface structure for stars other than our Sun (!)

constraining
  - convection and pulsation motions
  - dust growth
  - wind acceleration
  - mass-loss rates

and heading for a deeper understanding of the dynamics of evolved stars.
Theoretical models

Freytag et al. (2017)
star-in-a-box models

surface granulation due to convection