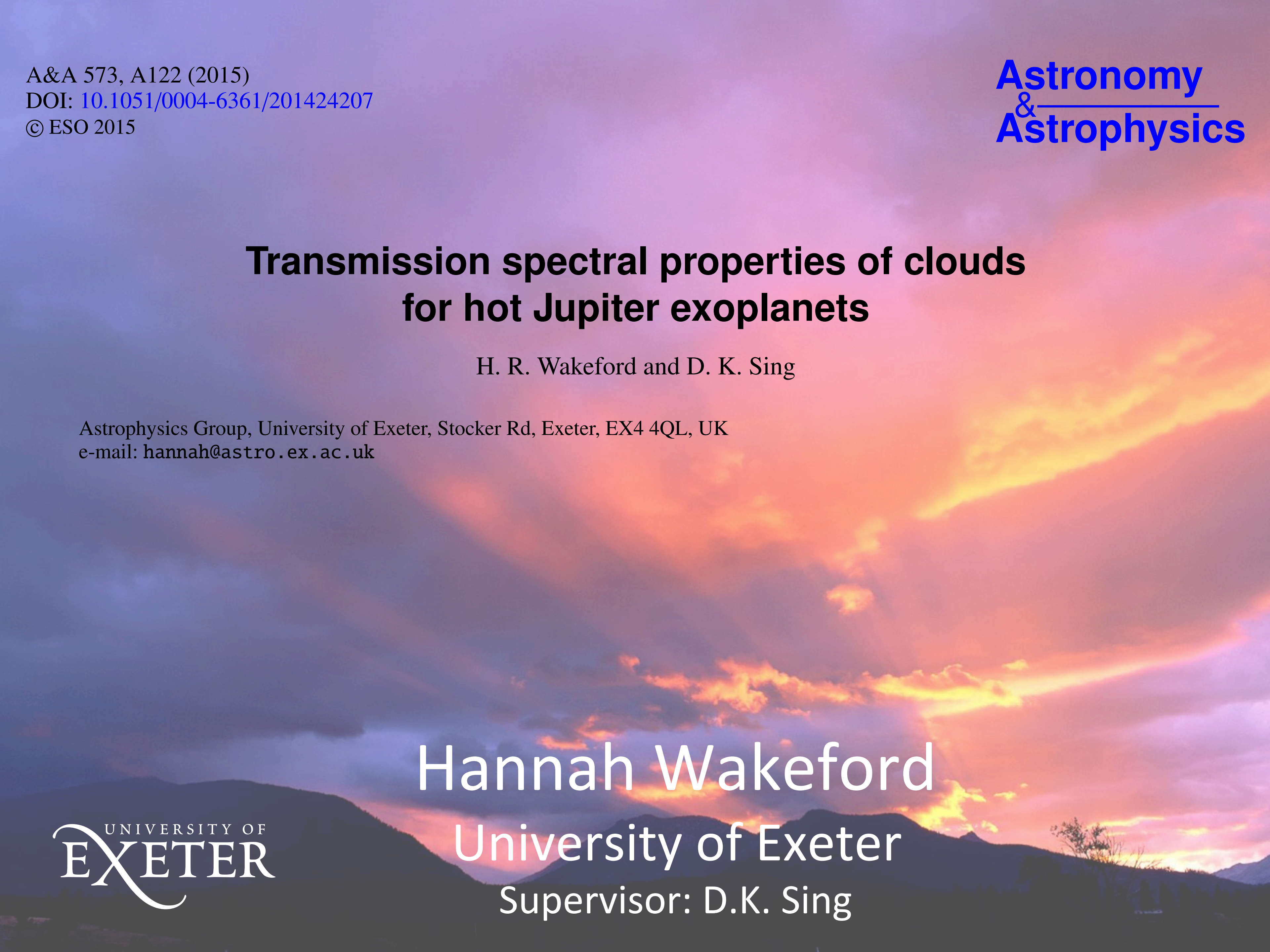

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Astronomy & Astrophysics

Transmission spectral properties of clouds for hot Jupiter exoplanets

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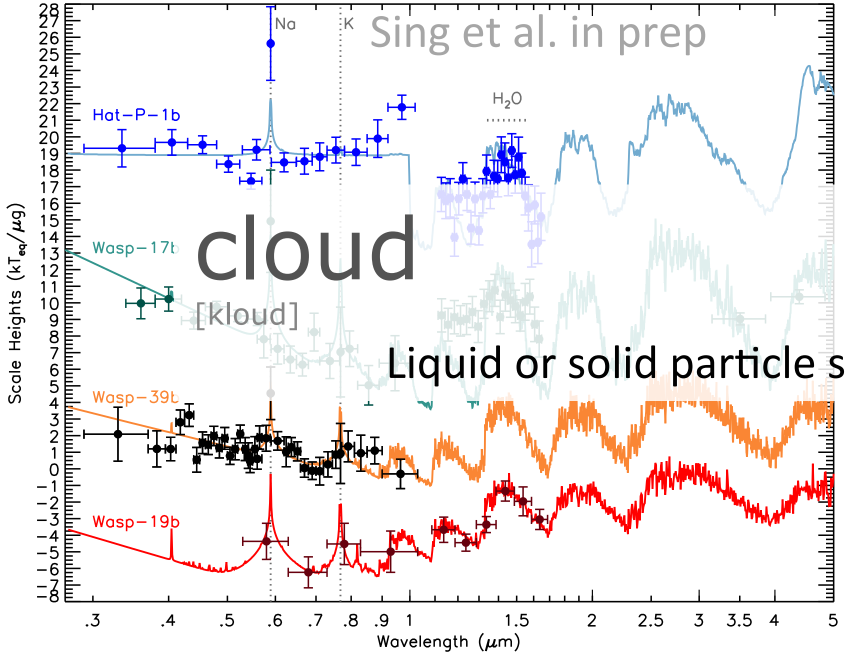
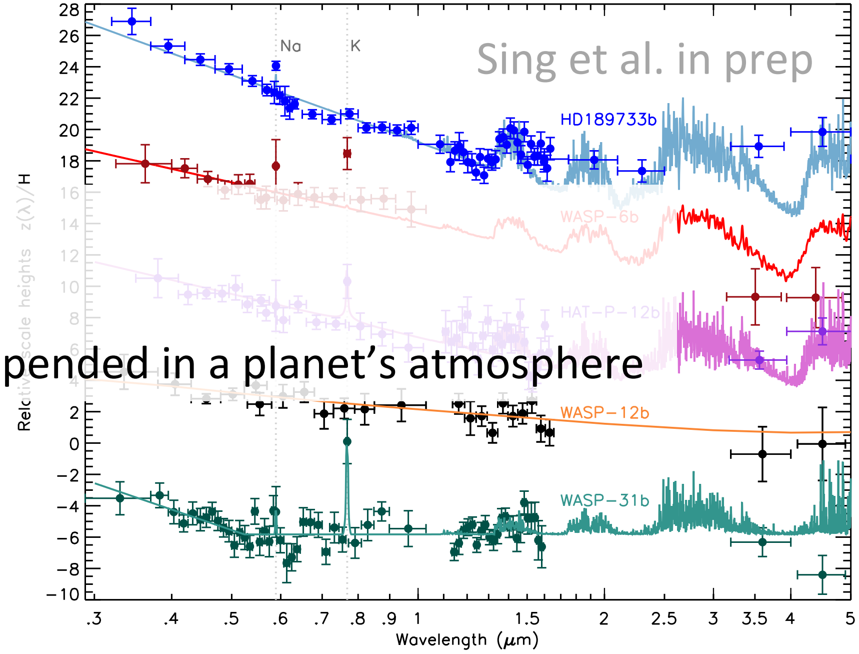
Observations of exoplanet atmospheres

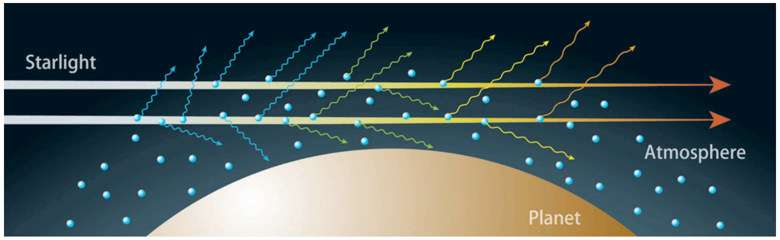


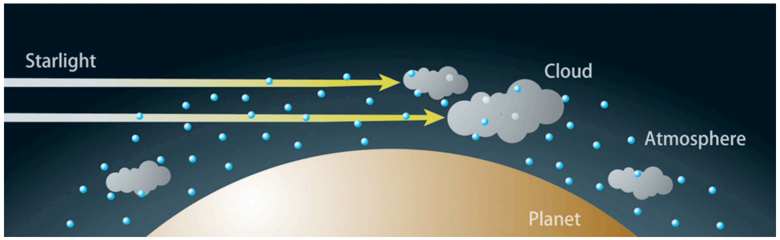


cloud

[kloud]

Liquid or solid particle suspended in a planet's atmosphere





Clear → **Cloudy/Hazy**

Wakeford et al. 2013
Line et al. 2013
Nikolov et al. 2014
Huitson et al. 2013

Pont et al. 2008
McCullough et al. 2014
Nikolov et al. 2015
Sing et al. 2013

Sing et al. 2015
Ballester et al. in prep
Sing et al. in prep
Fortney et al. (2010)

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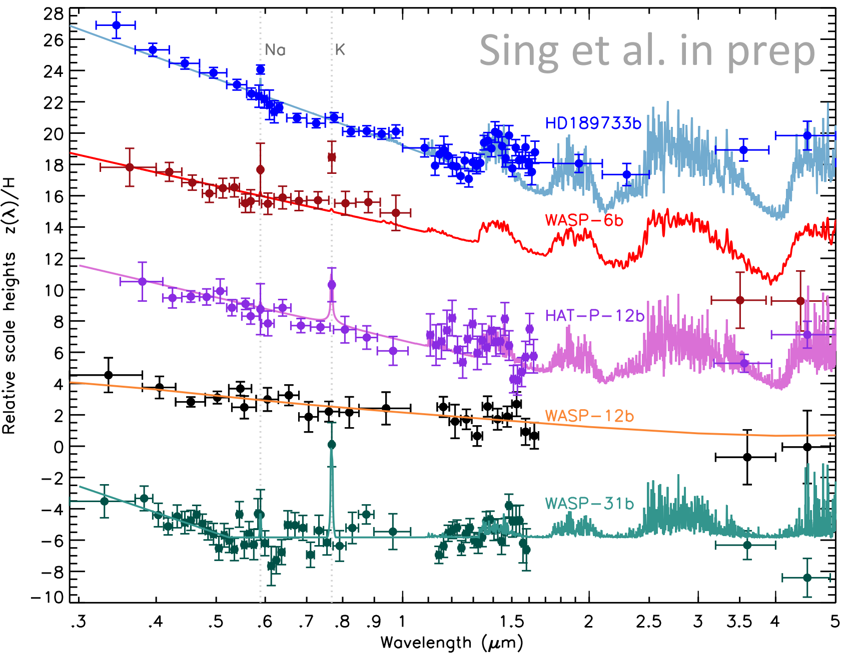
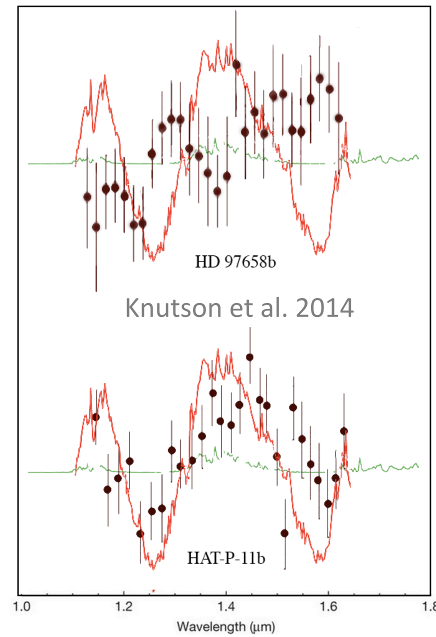
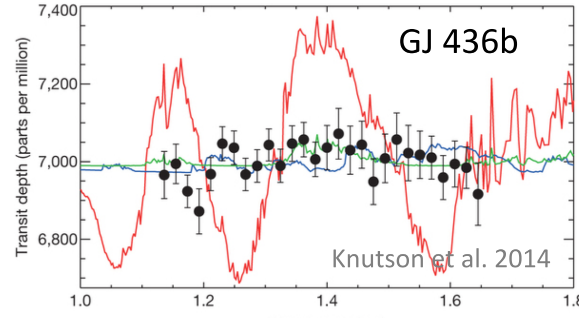
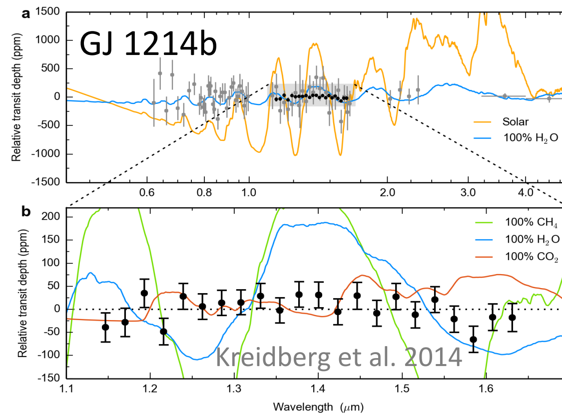
Clouds in exoplanet atmospheres?

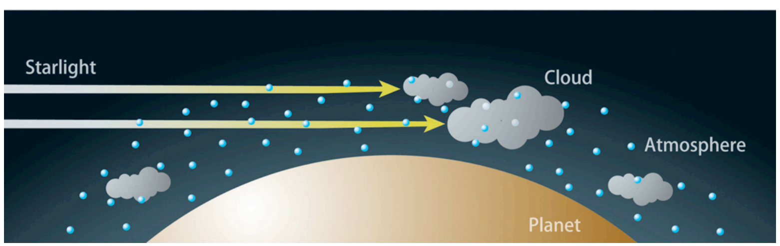
Clouds obscure absorption features across the optical and often near-IR









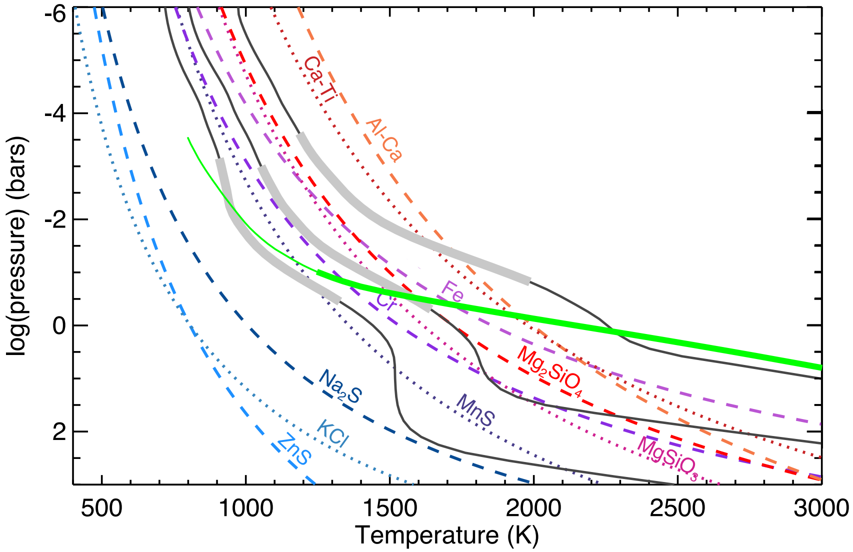


Cloudy/Hazy

ISM and Brown dwarf studies have shown that it is possible to differentiate between spectral absorption of different species

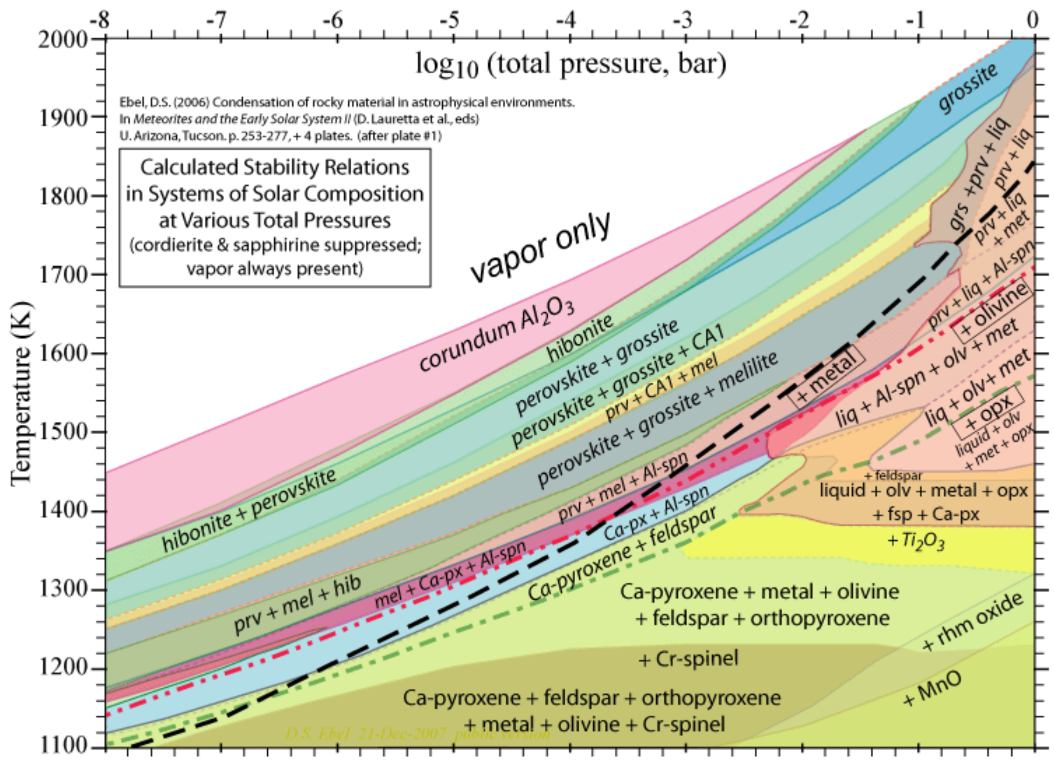
Wakeford & Sing, 2015, A&A, 573, A122

Potential cloud condensates



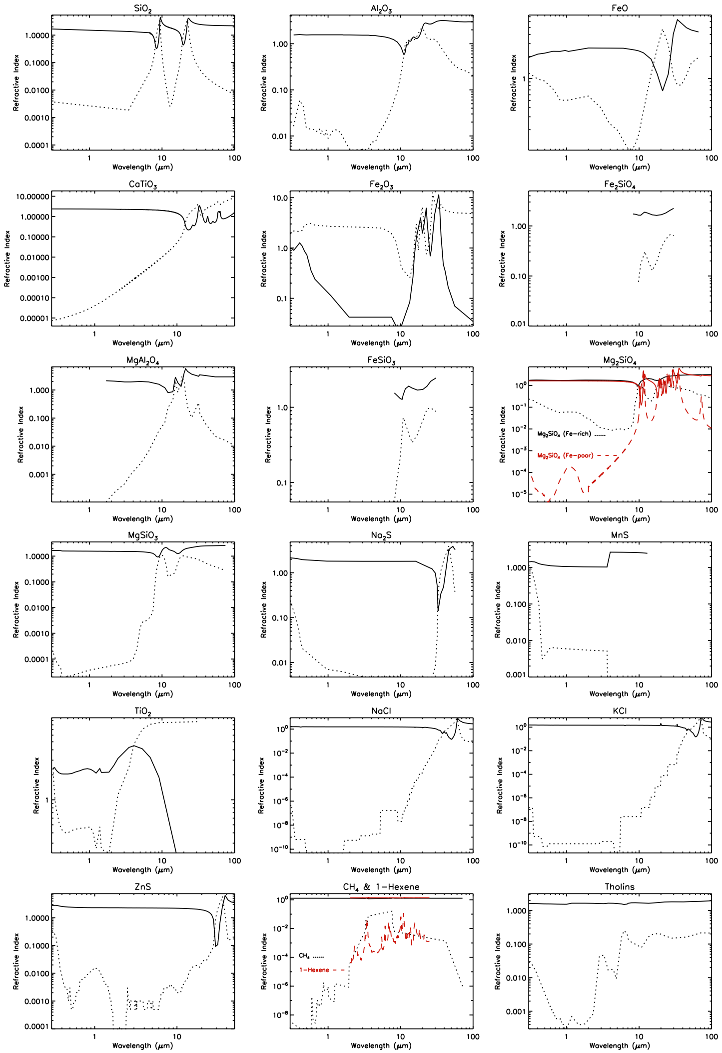
Condensation curves calculated following equations outlined in Visscher et al. (2010) and Morley et al. (2012). P-T profiles for three hot Jupiters from Fortney et al. (2010).

Clouds are expected to form where the condensation curve crosses the P-T profile of the planetary atmosphere.



Transmission spectroscopy probes the atmosphere around the mbar pressure level, which is indicated on the three exoplanet P-T profiles.

Optical Properties of condensates



Wakeford & Sing (2015)

Table 1: Table of references for n and k index for a number of condensates expected to form clouds in the upper atmosphere of hot Jupiters.

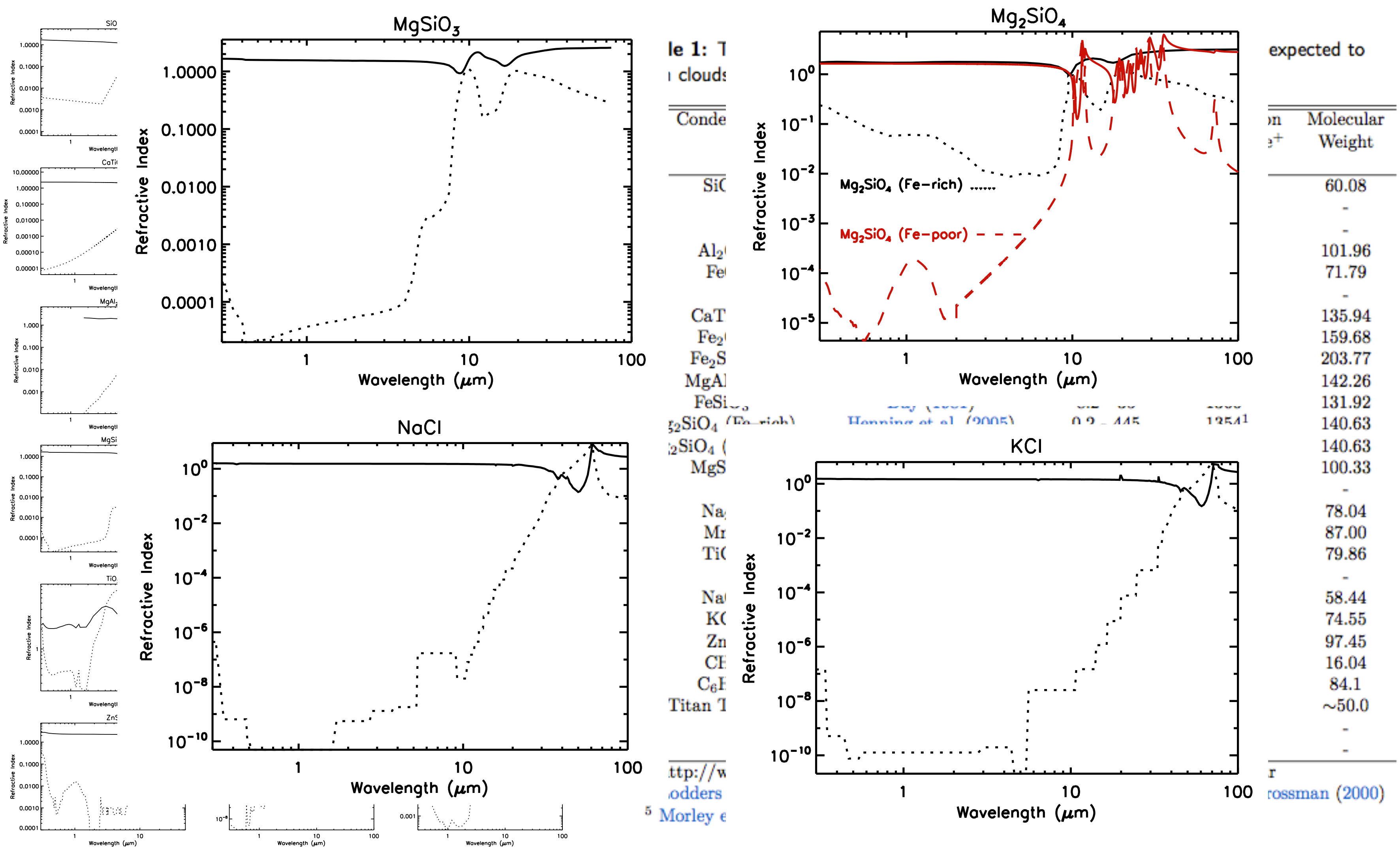
Condensate	Reference n, k index	λ Range (μm)	Condensation Temperature$^+$ (K)	Molecular Weight
SiO_2	Palik (1998)	0.04 - 11	1725	60.08
	Andersen et al. (2006)	7 - 28	-	-
	M. Meinecke (2005)*	6.6 - 10000	-	-
Al_2O_3	Koike et al. (1995)	0.3 - 150	1677[1]	101.96
FeO	Begemann et al. (1995)	10 - 100	1650[4]	71.79
	Andersen et al. (2006)	15 - 40	-	-
$CaTiO_3$	Posch et al. (2003)	2 - 155	1582[1]	135.94
Fe_2O_3	M. Meinecke (2005)*	0.1 - 987	1566	159.68
Fe_2SiO_4	Day (1981)	8.2 - 35	1443[4]	203.77
$MgAl_2O_4$	M. Meinecke (2005)*	1.6 - 270	1397[1]	142.26
$FeSiO_3$	Day (1981)	8.2 - 35	1366[4]	131.92
Mg_2SiO_4 (Fe–rich)	Henning et al. (2005)	0.2 - 445	1354[1]	140.63
Mg_2SiO_4 (Fe–poor)	Zeidler et al. (2011)	0.19 - 800	1354[1]	140.63
$MgSiO_3$	Egan & Hilgeman (1975)	0.1 - 0.4	1316[1]	100.33
	Dorschner et al. (1995)	0.5 - 80	-	-
Na_2S	Morley et al. (2012)	0.03 - 73	1176	78.04
MnS	Huffman & Wild (1967)	0.1 - 3	1139[2]	87.00
TiO_2	Kangarloo (2010a)	0.3 - 1.2	1125[2]	79.86
	Kangarloo (2010b)	1.3 - 30	-	-
NaCl	Palik (1998)	0.04 - 1000	825[3]	58.44
KCl	Palik (1998)	0.02 - 200	740[3]	74.55
ZnS	Querry (1987)	0.2 - 167	700[5]	97.45
CH_4	Martonchik & Orton (1994)	0.02 - 72	~80	16.04
C_6H_{12}	Anderson (2000)	2.0 - 25	68	84.1
Titan Tholins	Khare et al. (1984)	0.01 - 0.2	≤90	~50.0
	-	1.1 - 1000	-	-
	Ramirez et al. (2002)	0.2 - 1	-	-

* http://www.astro.uni-jena.de/Laboratory/OCDB/oxsul.html; $^+$ at 10^{-3} bar
[1] Lodders (2003), [2] Grossman (1972), [3] Burrows & Sharp (1999), [4] Ebel & Grossman (2000)
[5] Morley et al. (2012)

Wakeford & Sing (2015)

Wakeford & Sing, 2015, A&A, 573, A122

Optical properties of condensates



Wakeford & Sing (2015)

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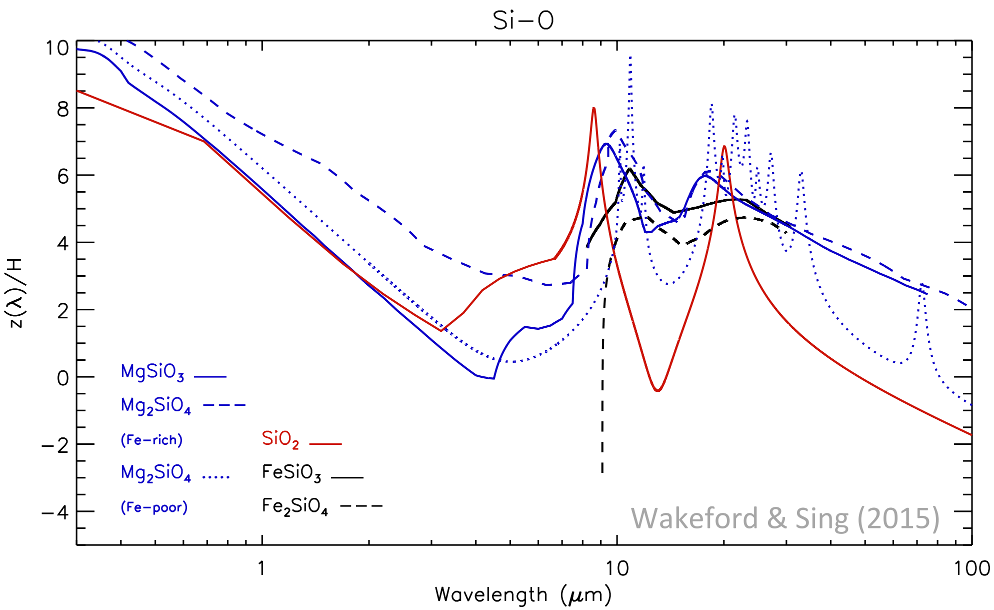
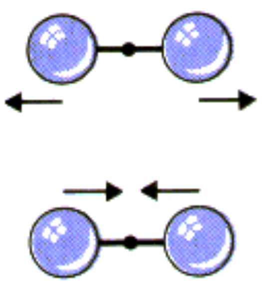
Vibrational modes



Absorption features are dominated by vibrational modes of the major di-atomic bond in the condensate.



Vibrational motion along the bond between two atoms

$$\nu = \frac{1}{2\pi c}\sqrt{\frac{K}{\mu_M}}$$

Table 4.3.1: Table of vibrational modes for the major diatomic bond species in the different cloud condensates considered in this paper.

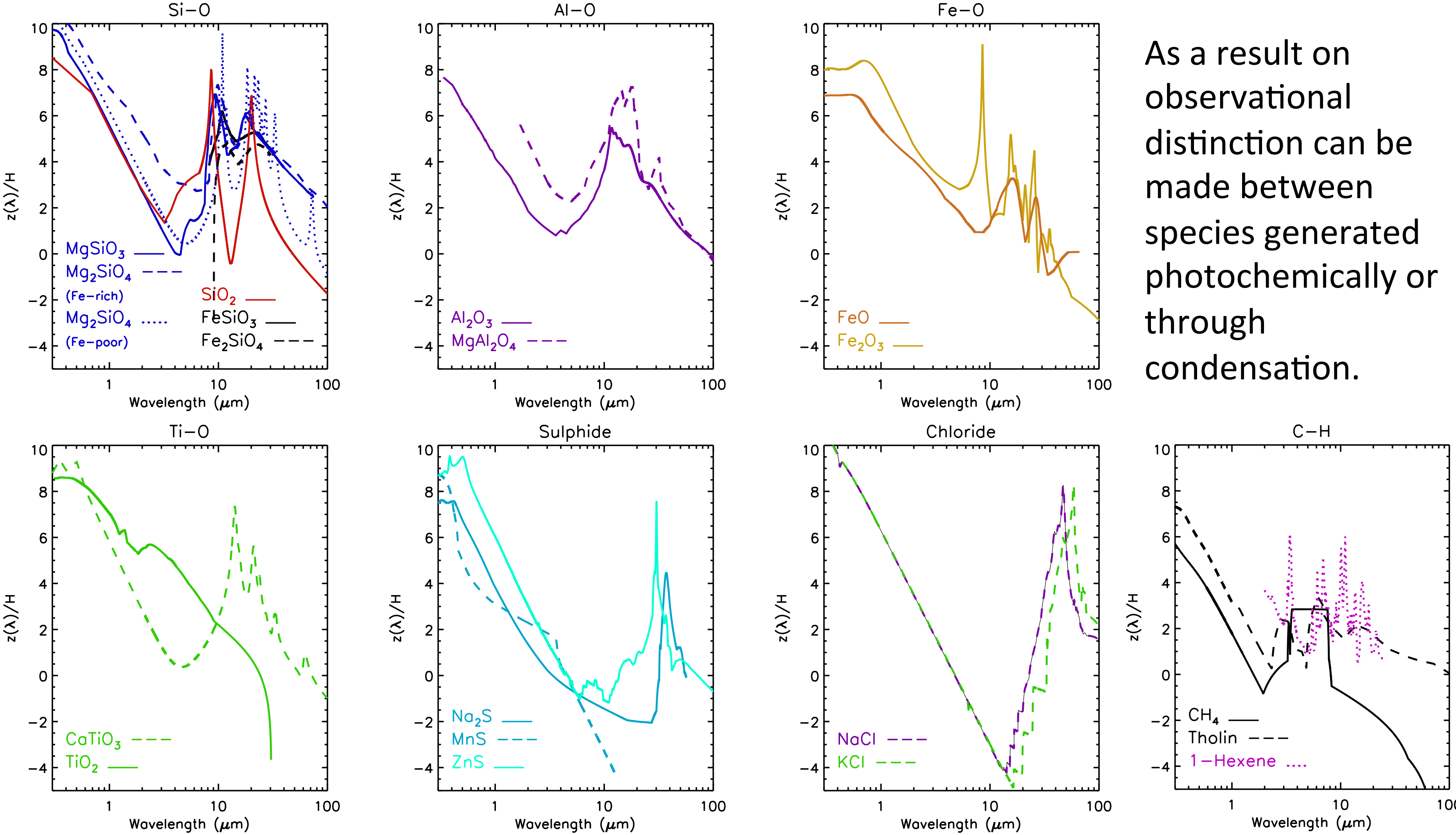
Major Bond	Reduced Mass, μ_M (g)	Vibrational Frequency, ν (cm^{-1})	Wavelength, λ (µm)
Si - O	10.192	1110 - 830[a]	9 - 12
Al - O	10.043	1100 - 350[c]	9 - 28.7
Fe - O	12.436	790[b]	12.5
Ti - O	11.99	850 - 150[d]	11.7 - 66
MnS	20.247	295-220[e]	33.8-45.4
ZnS	21.51	464[f]	21.5
NaCl	13.95	366[g]	27.32
KCl	18.60	281[g]	35.5
C - H	0.923	3032[a]	3.3

[a]Glassgold & Graham (2008); [b]Lehnert et al. (2002)
[c]Saniger (1995); [d]Gillet et al. (1993)
[e]Batsanov & Derbeneva (1969); [f]Kröger & Meyer (1954)
[g]Rice & Klemperer (2004)

Wakeford & Sing (2015)

Wakeford & Sing, 2015, A&A, 573, A122

Transmission Spectra of cloud condensates

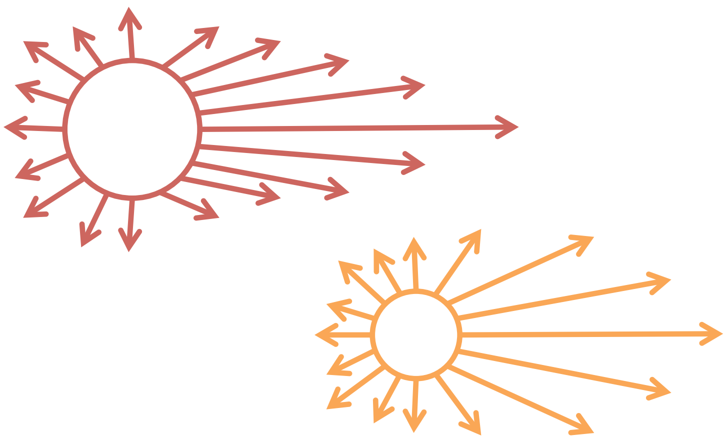


As a result on observational distinction can be made between species generated photochemically or through condensation.

Wakeford & Sing (2015)

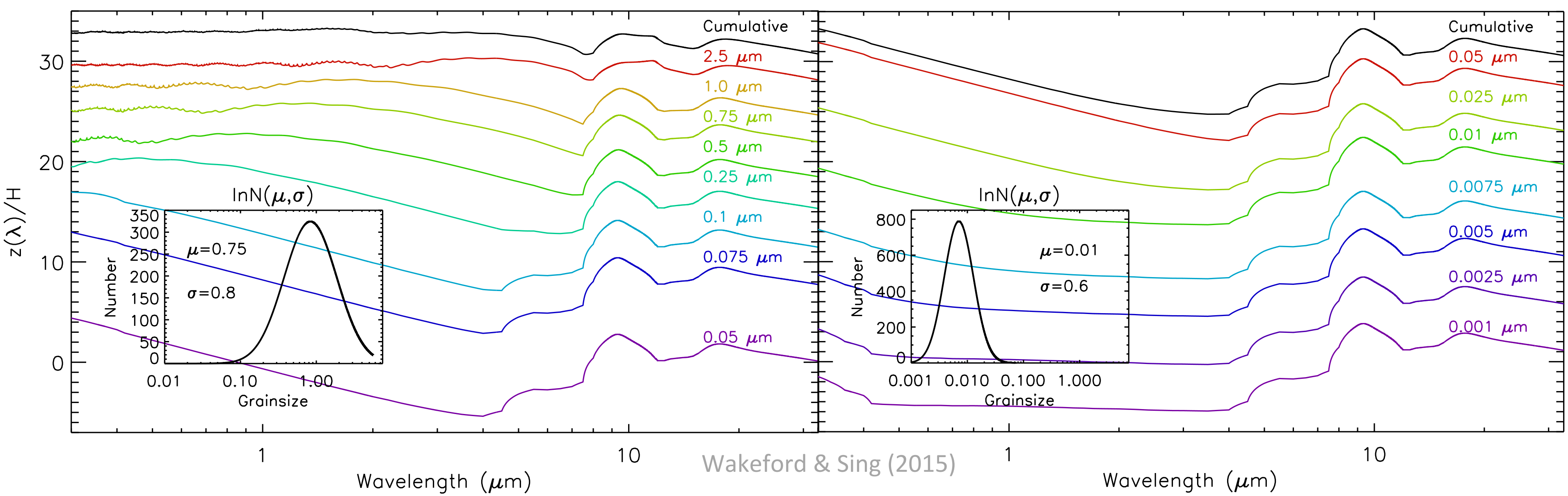
Wakeford & Sing, 2015, A&A, 573, A122

Particle size distributions



Rayleigh cross-section α a^6

This results in the transmission spectrum largely dependent on the largest grain size in the particle distribution.



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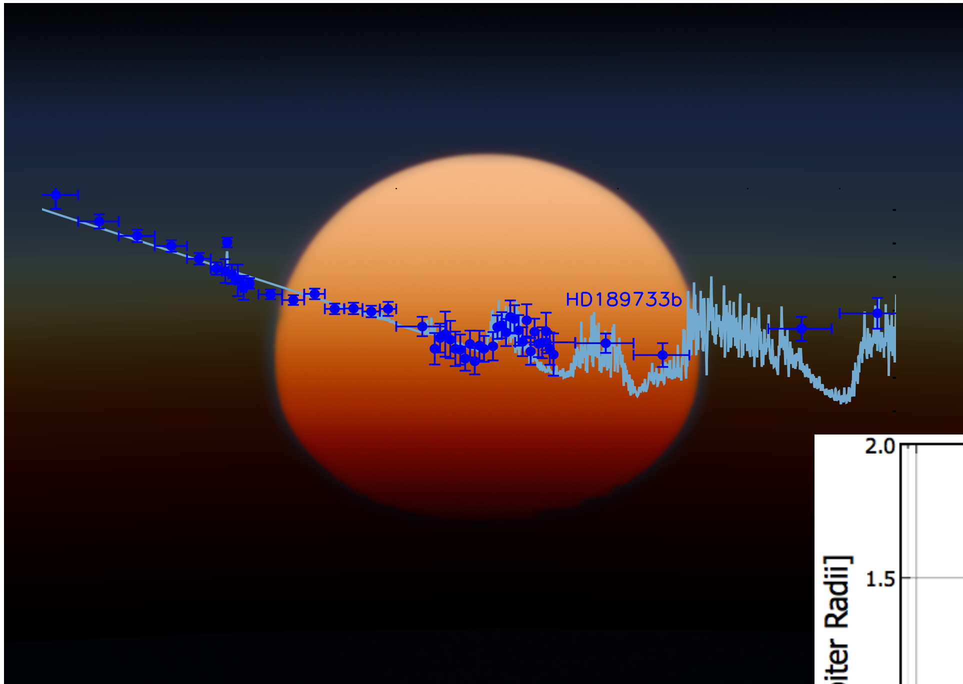
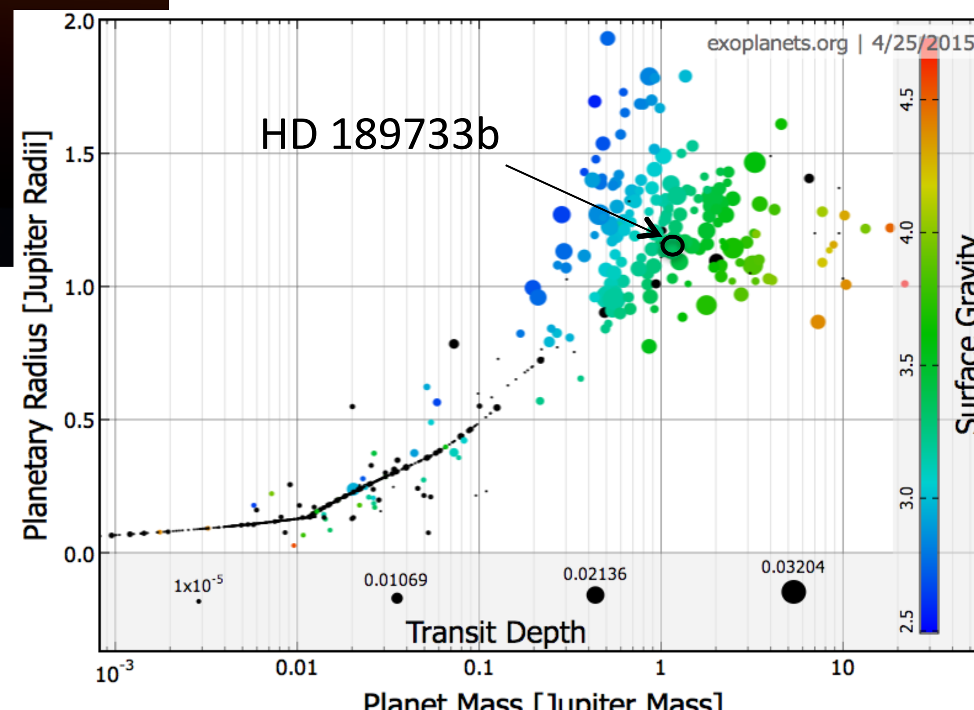
Hot Jupiter transmission spectra



We use HD 189733b as an example hot Jupiter.



HD 189733b's atmosphere shows strong Rayleigh scattering below 1μm and little indication of the expected alkali metal lines. (Pont et al. 2008)

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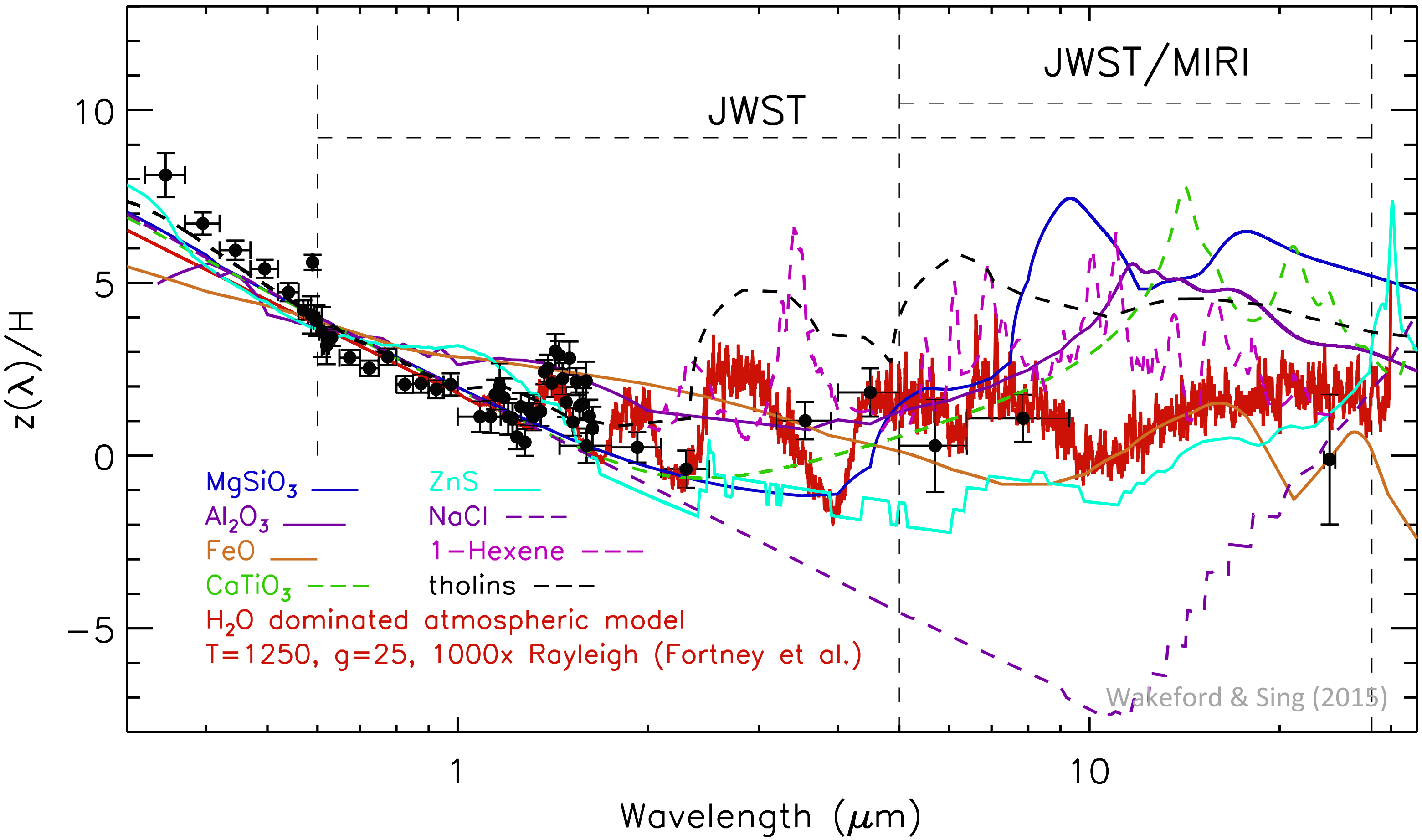
Condensate transmission spectra

Rayleigh scattering in the optical can be used as a diagnostic for particle size and condensates to be observed in the IR.



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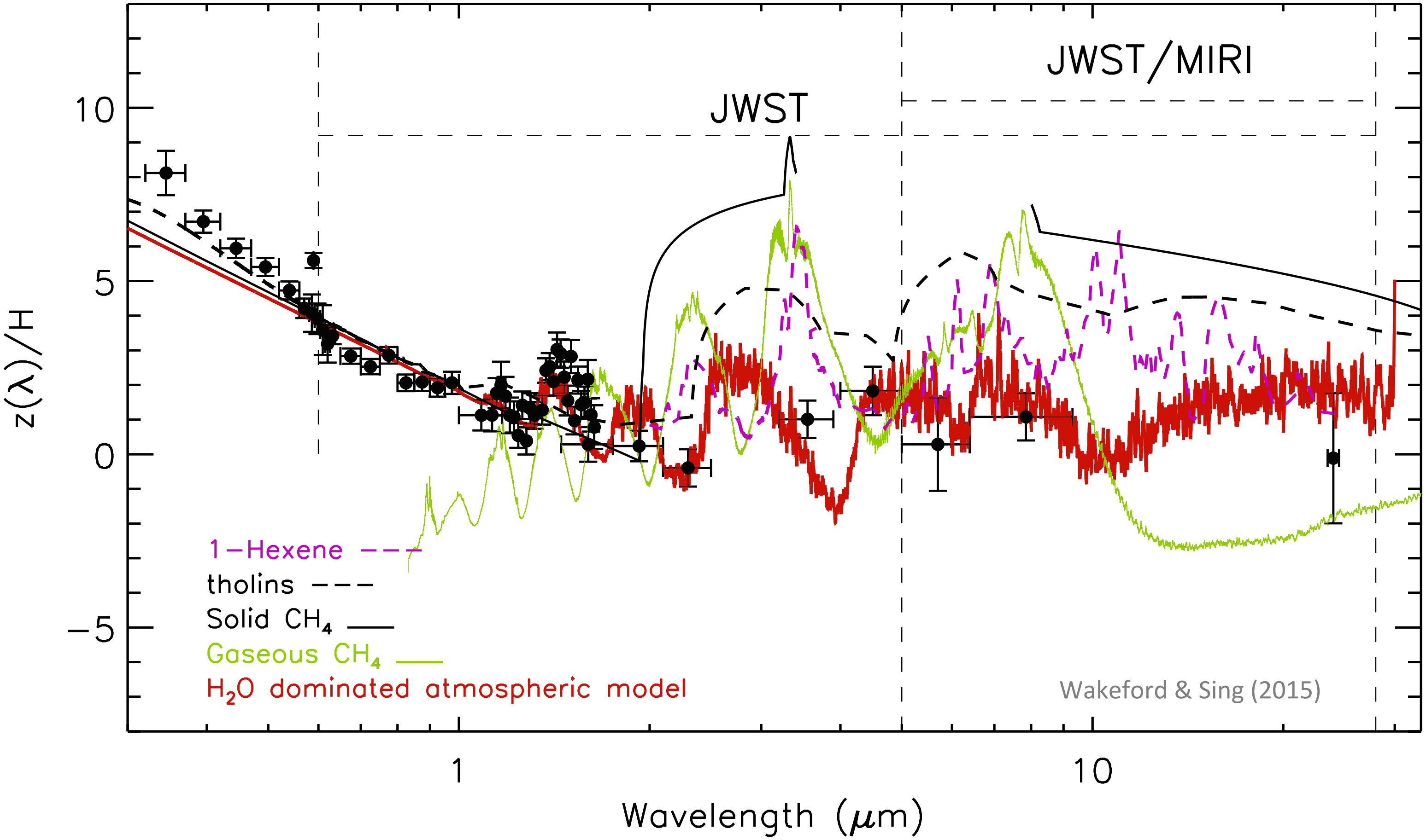
C-H gaseous vs. condensate

Some notable condensate features may be used to differentiate between gaseous and solid particle spectra



CH_4 Yurchenko & Tennyson (2014)

Amundsen et al. (2014)

C_2H_4 Sharp & Burrows (2007)

Rothman et al. (2009)

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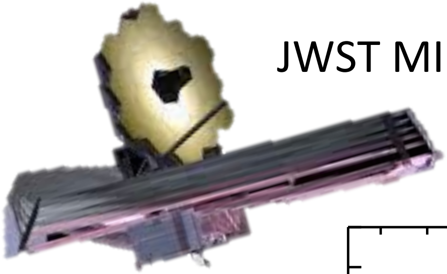
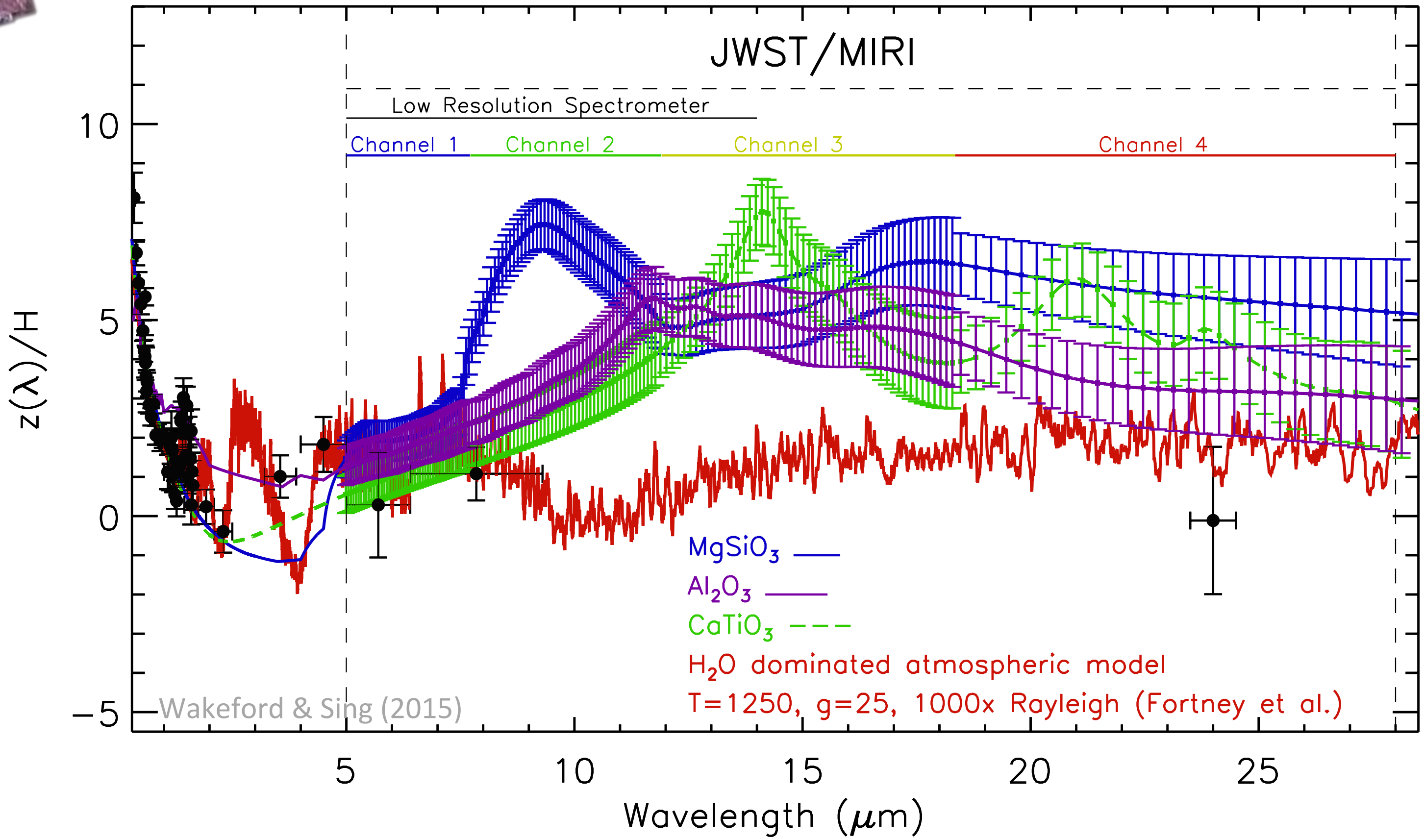
James Webb Space Telescope

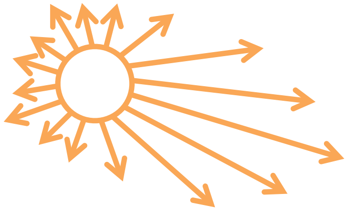


JWST MIRI will have 50x sensitivity and 7x angular resolution of Spitzer.

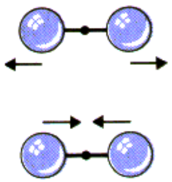


Wakeford & Sing, 2015, A&A, 573, A122

Summary



- Condensate transmission spectra can be approximated using the largest particle size in a distribution.



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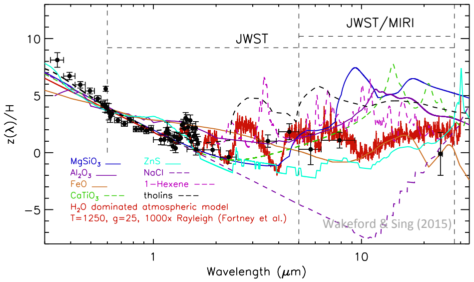
- As a result on observational distinction can be made between species generated photochemically or through condensation.



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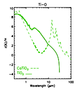
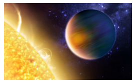
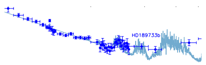
- JWST MIRI will have 50x sensitivity and 7x angular resolution of Spitzer.







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What’s Next?

NPP Fellow
working with Avi Mandell