Fundamental (Sub)stellar Parameters: Metallicity

PHY 688, Lecture 12
Outline

• Review of previous lecture
  – pressure broadening as an indicator of surface gravity
  – lower-gravity objects are younger, less massive
• Curve of growth: dependence of absorption line strength on abundance
  – determining photospheric abundances
• Metallicity (i.e., chemical content)
  – metal-poor dwarfs, a.k.a. “subdwarfs”
Previously in PHY 688...
Given Masses and Radii, Estimate Densities, Surface Gravities

- Gl 229B (T6.5)

\[ M \approx 0.03M_{\text{Sun}} \]
\[ R \approx 0.1R_{\text{Sun}} \]
\[ \bar{\rho} \approx 30\bar{\rho}_{\text{Sun}} \]
\[ \approx 40 \text{ g/cm}^3 \]
\[ \log g \approx 5 \]
Given Masses and Radii, Estimate Densities, Surface Gravities

- 2MASS 0535–0546B
  - secondary of first eclipsing substellar binary

\[
M = 0.034 M_{\text{Sun}} \\
R = 0.51 R_{\text{Sun}} \\
\bar{\rho} = 0.26 \bar{\rho}_{\text{Sun}} \\
= 0.36 \text{ g/cm}^3 \\
\log g = 3.6
\]
At Constant Mass Younger Brown Dwarfs Have Lower Gravities

2M 0535–05A (0.054 $M_{\text{Sun}}$)

2MASS 0535–0546B (0.034 $M_{\text{Sun}}$)

Gl 229B (~0.03 $M_{\text{Sun}}$)

(Burrows et al. 2001)
At Constant $T_{\text{eff}}$ Lower-Gravity (Younger) Brown Dwarfs Are Less Massive

(Burrows et al. 2001)
At constant $T_{\text{eff}}$, younger brown dwarfs have lower gravities (Burrows et al. 1997).

Substellar objects could be planets.

Lower gravity substellar objects could be planets.

(Burrows et al. 1997)
Luminosity (i.e., Surface Gravity) Effects at A0

(figure: D. Gray)
From Lecture 5: Line Profiles

- Natural line width (Lorentzian [a.k.a., Cauchy] profile)
  - Heisenberg uncertainty principle: $\Delta \nu = \Delta E / h$
- Collisional broadening (Lorentzian profile)
  - collisions interrupt photon emission process
  - $\Delta t_{\text{coll}} < \Delta t_{\text{emission}} \sim 10^{-9} \text{ s}$
  - dependent on $T$, $\rho$
- Pressure broadening ($\sim$ Lorentzian profile)
  - $\Delta t_{\text{interaction}} > \Delta t_{\text{emission}}$
  - nearby particles shift energy levels of emitting particle
    - Stark effect ($n = 2, 4$)
    - van der Waals force ($n = 6$)
    - dipole coupling between pairs of same species ($n = 3$)
    - dependent mostly on $\rho$, less on $T$
- Thermal Doppler broadening (Gaussian profile)
  - emitting particles have a Maxwellian distribution of velocities
- Rotational Doppler broadening (Gaussian profile)
  - radiation emitted from a spatially unresolved rotating body
- Composite line profile: Lorentzian + Gaussian = Voigt profile

\[
I_v = I_0 \frac{\gamma / 2\pi}{\left(\nu - \nu_0\right)^2 + \gamma^2 / 4}
\]
\[
\gamma \equiv \text{Lorentzian FWHM}
\]
\[
\gamma_{\text{natural}} = \frac{\Delta E_i + \Delta E_f}{h / 2\pi} = \frac{1}{\Delta t_i} + \frac{1}{\Delta t_f}
\]
\[
\gamma_{\text{collisional}} = 2 / \langle \Delta t_{\text{coll}} \rangle
\]
\[
\gamma_{\text{pressure}} \propto \langle r \rangle^{-n}; \quad n = 2, 3, 4, 6
\]
\[
I_v = \frac{1}{\sqrt{2\pi} \Gamma} e^{-\frac{(\nu - \nu_0)^2}{2\Gamma^2}}
\]
\[
\Gamma \equiv \text{Gaussian FWHM}
\]
\[
\Gamma_{\text{thermal}} = \nu_0 \sqrt{\frac{kT}{mc^2}}
\]
\[
\Gamma_{\text{rotational}} = 2\nu_0 u / c
\]
Gravity in UCDs

Key species:

- neutral alkali elements (Na, K)
  - weaker at low $g$

- hydrides
  - CaH weaker at low $g$
  - FeH unchanged

- oxides
  - VO, CO, TiO
    - stronger at low $g$
  - $H_2O$ ~ unchanged

$log g$ and $T_{eff}$ are measurable properties

Feb 20, 2009  (Kirkpatrick et al. 2006)
Example: HR8799bcd – Do the “Planets” Have Planetary Masses?

Keck AO image of the HR 8799bcd planetary system
(Marois et al. 2008, Science)
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  – metal-poor dwarfs, a.k.a. “subdwarfs”
Alkali (Na, K) lines in visible spectra of late-L and T dwarfs become saturated!
Lorentzian Line Profile at Increasing $\tau$

simulation for the H$\alpha$ line profile
Lorentzian Line Profile at Increasing $\tau$

simulation for the H$\alpha$ line profile

saturation at $\tau > 5$
Lorentzian Line Profile at Increasing $\tau$

simulation for the H$\alpha$ line profile
Lorentzian vs. Gaussian Line Profiles: Small $\tau$

simulation for the H$\alpha$ line profile
Lorentzian vs. Gaussian Line Profiles: Large $\tau$

- simulation for the H\(\alpha\) line profile
  - core more sensitive to Gaussian parts
  - wings more influenced by Lorentzian parts
Curve of Growth: Dependence of Line Equivalent Width $W$ on Column Density $N$

- $N \equiv$ integral of number density of absorbing atoms or molecules along line of sight [cm$^{-2}$]
  - for small $N$, $W \propto N$
    - **linear** part of the curve of growth
  - for larger $N$, $W \propto \sqrt{\ln N}$
    - after the Gaussian core bottoms out
    - **flat** part of the curve of growth
  - for even larger $N$, $W \propto \sqrt{N}$
    - after the absorption by the Lorentzian wings becomes strong
    - **square root** part of the curve of growth

- There is a different curve of growth, $W(N)$, for each spectral line
Universal Curve of Growth

- the ratio of $W$ to Doppler line width $\Delta \lambda$ depends upon the product of $N$ and a line’s oscillator strength $f$ in the same way for every spectral line (e.g. Unsöld 1955).

$$\log \left( \frac{W}{\Delta \lambda} \right) \quad \begin{align*}
0 & \quad \text{linear} \\
1 & \quad \text{flat} \\
-1 & \quad W \propto N \\
\end{align*}$$

$$\log (Nf) \quad \begin{align*}
0 & \quad W \propto \sqrt{\text{ln} \, N} \\
3 & \quad W \propto \sqrt{N} \\
\end{align*}$$

$$\Delta \lambda = \frac{\lambda v}{c} = \frac{\lambda}{c} \sqrt{\frac{2kT}{m}}$$
Alkali (Na, K) lines in visible spectra of late-L and T dwarfs become saturated!

(Kirkpatrick 2005)
Curve of Growth: Determining Abundances

• Measure $W$ for a lot of lines (each with distinct, known $f$) of a bunch of atomic or ionic species.

• Plot $W/\Delta \lambda$ against $xNf$ where:
  – $N$ is the column density of one species
  – $x$ is the relative abundance of the atomic species that gives rise to the line (ratio of number density of that species to the number density of the first species),

• Adjust $x$, $N$, and $\Delta \lambda$ until the points fit the universal curve of growth.

• Then one knows these three quantities for each species.
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Solar Abundance Distribution:
\[ \log(H) = 12.0 \]
Metallicity

\[ [m/H]_* = \log N(m)_*/ \log N(H)_* - \log N(m)_{\text{Sun}}/ \log N(H)_{\text{Sun}} \]

- \([\text{Fe/H}]_{\text{Sun}} = 0.0\) is the solar Fe abundance
- \([\text{Fe/H}] = -1.0\) is the same as 1/10 solar

\[ [m/\text{Fe}]_* = \log N(m)_*/ \log N(\text{Fe})_* - \log N(m)_{\text{Sun}}/ \log N(\text{Fe})_{\text{Sun}} \]

- \([\text{Ca/Fe}] = +0.3\) means twice the number of Ca atoms per Fe atom

- Sun’s metal content is \(\approx 1.6\%\) by mass
The Early Universe Had No Heavy Elements

(figure credit: N. Wright, UCLA)
Metal Enrichment Is Due to Stars

- **nuclear fusion**
- **neutron capture**

Log(Abundance) by Number

Atomic Number
Stellar Populations

- Young stars (Pop I) are metal-rich
  - $[\text{m/H}] > -2.0$
  - Milky Way disk, spiral arms
- Old stars (Pop II) are metal-poor
  - $[\text{m/H}] < -2.0$
  - Milky Way halo, bulge
- Ancient stars (Pop III) are expected to have been nearly metal-free (at birth)
Cool Metal-Poor Stars

- M-type metal-poor stars are most numerous
  - M (+L) stars are longest lived
- \(dM\): normal M dwarfs, \([m/H] > -1\)
- \(sdM\): M subdwarfs, \(\langle [m/H] \rangle \sim -1.3\)
- \(esdM\): M extreme subdwarfs, \(\langle [m/H] \rangle \sim -2\)
  - i.e., Pop II
- \(usdM\): M ultra subdwarfs, \(\langle [m/H] \rangle < -2\)
  - also Pop II
Cool Metal Poor Stars

- lower atmospheric opacity of subdwarfs reveals the deeper, hotter layers of these stars
- a dM and an sdM star of the same mass have approximately the same luminosity, but the sdM star can be up to 700 K hotter
- subdwarfs : dwarfs $\sim 1 : 400$ (in Milky Way)
- identified by their high velocities relative to Sun
  - kinematics characteristic of galactic halo stars
Subdwarf SEDs

- signatures of metal deficiencies
- higher gravity in deeper layers?

\[ dM \quad [m/H]=0.0 \]
\[ esdM \quad [m/H]=-2.0 \]
\[ usdM \quad [m/H]=-4.0 \]

\( T_{\text{eff}}=3500, \ logg=5.0 \)

(Jao et al. 2008)
enhanced hydrides, $H_2$
Relevance to Brown Dwarfs

• Do substellar subdwarfs exist?

• H-burning mass limit is higher at lower metallicity

• sdL’s: recently discovered, <10 known
  – latest is sdL7: likely substellar

• sdT’s?
  – one reported, but unusual spectrum could be explained by other factors (e.g., high surface gravity)
Relevance to Planets

- Can planets form in metal-poor environments?
- Leading theories for planet formation
  - core accretion
    - gradual accretion of rocky material, potentially followed by gas accretion
  - disk instability
    - rapid gravitational collapse within a cooling gaseous disk