Infrared Extinction Law 
& 
Very Large Dust Grains

Biwei Jiang 姜碧沩
bjiang@bnu.edu.cn
Dept of Astronomy, Beijing Normal University, China

Collaborators: Aigen Li, Jian Gao, Shu Wang, Mengyao Xue, Zhenzhen Shao
Scattering: error or variation?

\[ \frac{A_\lambda}{A_{Ks}} \]

- WD01 $R_v = 3.1$
- MRN $R_v = 3.1$

- Wang et al. (2013)
- Nishiyama et al. (2009)
- Gao et al. (2009)
- Flaherty et al. (2007)
- Jiang et al. (2006)
- Indebetouw et al. (2005)
- Lutz (1999)

Wang, Li & Jiang 2014 PSS

$\lambda$ (\(\mu\)m)
Uncertainty of the intrinsic color of the photometric method
Contamination:
YSO, AGB stars and dwarf stars with similar colors

Red giants
Red clump stars

Gao, Jiang & Li 2009
Dispersion of intrinsic color index

\begin{align*}
\text{Majewski et al. 2011} & \quad \text{Rayleigh Jeans Color Excess} \\
H-[4.5] &= 0.08
\end{align*}
Our improvement

• Determine the intrinsic color index for each star individually rather than assuming a constant index
  • Large-scale spectroscopic surveys: SDSS/APOGEE, LAMOST
  • K-, G-type red giant stars
Intrinsic color index: the blue edge method

Main Sequence

Ducati (2001)
The APOGEE Spectroscopic Survey

• SDSS/DR12
• >100,000 red giant stars to magnitude $H=12.2$
• Resolution $R=\lambda/\Delta\lambda \sim 22,500$
• Typical $S/N > 100$
• Stellar parameters: $\log g<3.0$, $T_{\text{eff}}$, $Z >-1.0$
• Spectral type: A, F, G, K
• $J_{\text{err}} <0.05$ mag, $Ks_{\text{err}} <0.05$ mag
• $V_{\text{SCATTER}} < 0.3$ km/s
• 63,330 stars
\[ C_{JKs}^0 = 20.285 \times \exp\left(\frac{-T_{\text{eff}}}{1214K}\right) + 0.209 \]
$C(K_S - [9])_{intrinsic} = 0.145 \times \left( \frac{T_{eff}}{1000 K} \right)^2 - 1.372 \times \left( \frac{T_{eff}}{1000 K} \right) + 3.419$

$[9]_{err} < 0.2 \text{ mag}$

1024 sources

188 (red)
\[ C_{KsW1}^0 = 0.041 \times \left( \frac{T_{\text{eff}}}{1000 \text{K}} \right)^2 - 0.388 \times \left( \frac{T_{\text{eff}}}{1000 \text{K}} \right) + 1.006 \]

\[ C_{KsW2}^0 = 0.029 \times \left( \frac{T_{\text{eff}}}{1000 \text{K}} \right)^2 - 0.208 \times \left( \frac{T_{\text{eff}}}{1000 \text{K}} \right) + 0.327 \]
\[ C_{KsW3}^0 = 9.634 \times 10^{10} \times \exp\left(\frac{-T_{\text{eff}}}{1340K}\right) + 0.103 \]

\[ C_{KsW4}^0 = 6.824 \times 10^3 \times \exp\left(\frac{-T_{\text{eff}}}{3580K}\right) + 0.135 \]
Linear fitting of color excesses

• Subtraction of the intrinsic color indexes
• Linear fitting of the color excesses \( E(Ks - \lambda) \) and \( E(J - Ks) \)
• Exclusion of outliers by 3 sigma criterion
  – Important for sources with silicate features
• Intercept
  – Nearly zero
• Conversion to \( A_\lambda/A_{KS} \) given \( \frac{A_J}{A_{KS}} = 2.72 \) from \( \frac{E(Ks-\lambda)}{E(J-Ks)} \)
Near-Infrared

\[ \frac{E_{JH}}{E_{JKs}} = 0.652 \]

\[ \frac{A_J}{A_{KS}} = 2.72, \alpha = 1.79 \]
Mid-Infrared

\[
E(Ks-W1) = 0.238 \cdot E(J-Ks) - 0.013 \\
A_{W1}/A_{Ks} = 0.591
\]

\[
E(Ks-W2) = 0.312 \cdot E(J-Ks) - 0.017 \\
A_{W2}/A_{Ks} = 0.463
\]

\[
E(Ks-W3) = 0.269 \cdot E(J-Ks) - 0.016 \\
A_{W3}/A_{Ks} = 0.537
\]

\[
E(Ks-W4) = 0.370 \cdot E(J-Ks) - 0.036 \\
A_{W4}/A_{Ks} = 0.364
\]
\begin{align*}
E(Ks-[3.6]) &= 0.260 \times E(J-Ks) - 0.012 \\
A_{[3.6]} / A_{Ks} &= 0.553 \\

E(Ks-[4.5]) &= 0.313 \times E(J-Ks) - 0.009 \\
A_{[4.5]} / A_{Ks} &= 0.461 \\

E(Ks-[5.8]) &= 0.355 \times E(J-Ks) - 0.014 \\
A_{[5.8]} / A_{Ks} &= 0.389 \\

E(Ks-[8.0]) &= 0.334 \times E(J-Ks) - 0.001 \\
A_{[8.0]} / A_{Ks} &= 0.426
\end{align*}
1. Consistent in 3-8μm, flat
2. Smaller than others
3. Agree with $R_v=5.5$ (WD01)

Xue et al. 2016
Varying or not?
Universality of the Near-IR Extinction Law

The dispersion can be fully explained by the error Pearson correlation coefficient of 0.03

Wang & Jiang 2014
No apparent variation in the mid-IR with $A_{KS}$

Xue et al. 2016

$\frac{A_{\alpha}}{A_{KS}}$

- $R_v=3.1$ (WD01)
- $R_v=5.5$ (WD01)
- $0.3 < A_{KS} < 1$, McClure (2009)
- $1 < A_{KS} < 7$, McClure (2009)
- Ice grain model, Wang et al. (2015a)

$A_{KS} < 0.5$, this work
$0.5 < A_{KS} < 1$, this work
$A_{KS} > 1$, this work
$A_{KS} < 0.5$, Chapman et al. (2009)
$0.5 < A_{KS} < 1$, Chapman et al. (2009)
$1 < A_{KS} < 2$, Chapman et al. (2009)
$A_{KS} > 2$, Chapman et al. (2009)
Alternatively, no extreme (very diffuse or very dense) environments are included.

\[ A_V \sim 6.0 \times E(J-K_s) \]
Silicate Profile around 10µm

• OB stars as tracers
  – Follow the Rayleigh-Jeans law in the mid-IR

  – No molecular lines or circumstellar dust (silicate or PAH spectral lines)
  – No free-free emission of ionized wind (7.5 µm Pfund α and 12.4 µm Humphries α emission lines)
  – Significant extinction (E_{JKs}>0.4)

  – 5 objects
Figure 13. An analytical fit to the observed interstellar extinction curve in the IR at $0.9 \lesssim \lambda \lesssim 15 \, \mu m$.  

Shao et al. 2018
Problem with the silicate profile

- Too small sample to conclude whether the profile changes and how
- 18um: not enough S/N ratio for the sample stars
- Sensitivity: JWST
Dust model

A dust grain is most efficient in extinction at the wavelength comparable to its size.
WD01 + micron-sized dust (graphite, silicate, iron)
The mid-IR extinction

\[ R_V = 3.1 \text{ sil.+gra/PAH+ \( \mu \)m-sized gra.} \]

\[ A_{\lambda}/N_H \ (10^{-22} \text{ mag cm}^2) \]

\[ \lambda (\mu\text{m}) \]

Wang, Li & Jiang 2015a
Emission

\[ \frac{\lambda I_\lambda}{N_H} \text{ (erg s}^{-1} \text{ sr}^{-1} \text{ H}^{-1}) \]

- **DIRBE**
- **FIRAS**
- **Planck**
- **Model**

- **Graphite + PAH**
- **Silicate**
- **μm-sized graphite**

\[ a_0 = 1.2 \mu m, \sigma = 0.3, C/H = 137 \text{ppm} \]
Abundance problem

• Our Model
  – \([C/H]_{\text{dust}} \approx 225 \text{ppm (UV/optical)} + 137 \text{(Mid-IR)} = 362 \text{ ppm}\)

• The proto-Sun abundance is \([C/H] \approx 288 \text{ ppm}\)
  – \(\sim 140 \text{ ppm in gas (Cardelli et al. 1996)}\)
  – \(\sim 100 \text{ ppm in gas (Sofia et al. 2011)}\)
  – Only \(\sim 148-188 \text{ ppm available for dust}\)

• The “C crisis” holds for all dust models!
  – \([C/H]_{\text{dust}} \approx 252 \text{ ppm (and } [\text{Si/H}]_{\text{dust}} \approx 47.5 \text{ ppm)}\)
    • (Weingartner & Draine 2001)
  – \([C/H]_{\text{dust}} \approx 244 \text{ ppm (and } [\text{Si/H}]_{\text{dust}} \approx 36 \text{ ppm)}\)
    • (Zubko et al. 2004)
  – \([C/H]_{\text{dust}} \approx 233 \text{ ppm (and } [\text{Si/H}]_{\text{dust}} \approx 50 \text{ ppm)}\)
    • (Jones et al. 2013)
$\text{H}_2\text{O}$ ice

![Graph showing the relationship between $A_{\lambda}/N_H$ ($10^{-22}$ mag cm$^2$) and wavelength ($\lambda$ in microns). The graph includes various symbols representing different references and curves for silicate, graphite+PAH, and $\mu$m-sized $\text{H}_2\text{O}$. The parameters $a_0=4.0\mu$m and $\sigma=0.4$, with $\text{O/H}=160$ ppm, are indicated.]
Summary

• Precise determination of the infrared extinction law
• The infrared extinction law shows no apparent variation
• The flatness of the 3-8um extinction curve can be accounted by incorporating the micron-sized water ice into the dust model
Thanks
References: Interstellar Extinction Law

1. A Precise Determination of the Mid-Infrared Interstellar Extinction Law Based on the APOGEE Spectroscopic Survey
   • Mengyao Xue, B. W. Jiang, Jian Gao, Jiaming Liu, Shu Wang, and Aigen Li
   • 2016, ApJS 224, 23

2. Universality of the Near-infrared Extinction Law Based on the Apogee Survey
   • Shu Wang and B. W. Jiang

3. The Ultraviolet Extinction in the GALEX Bands
   • Mingxu Sun, B.W. Jiang, He Zhao, Jian Gao, Shuang Gao, Mingjie Jian, Haibo Yuan
References: Dust modelling

• Wang, Li & Jiang 2015, MNRAS 454, 569
  The interstellar oxygen crisis, or where have all the oxygen atoms gone?

  Very large interstellar grains as evidenced by the mid-infrared extinction

• Wang, Li & Jiang 2014, PSS 100, 32
  Modeling the infrared interstellar extinction
Beijing Normal University, Dept. of Astronomy

• 31 faculty, 20 master and 8 PhD graduates yearly
• Cosmology, variable stars, solar physics, interstellar physics, gamma-ray burst, plasma experiment, astrometry
• International collaboration
  – Support by China Scholarship Council
    • About 4-5 graduate students annually
  – Funds, such as NSFC
  – Collaboration agreement with foreign universities, e.g. Leiden, Toulouse
Thanks
VERY LARGE INTERSTELLAR GRAINS
Very Large Grains (VLG)

- μm-sized
  - Geometrical-optics regime (i.e., $2\pi a/\lambda >> 1$) $\rightarrow$ “Gray” in the UV/optical $\rightarrow$ The UV/optical extinction is not able to constrain their quantity or size distribution.
- Are μm-sized grains present in the ISM?
  - Primitive meteorites $\rightarrow$ μm-sized presolar grains (graphite, SiC, Al$_2$O$_3$, Si$_3$N$_4$; Clayton & Nittler 2004)
  - Ulysses and Galileo in situ detection, radii up to $\sim$2.0 μm (Grün et al. 1994, Krüger et al. 2007)
  - Radar meteors, radii $\sim$20 μm (Taylor et al. 1996)
  - Stardust detection (Westphal et al. 2014, Sterken et al. 2015)
\[10^{29}N_H^{-1}a^{-4}dn/da \text{ (cm}^3/\text{H)}\]

- **Graphite + PAH** (dashed blue line)
- **Silicate** (dashed green line)
- **\(\mu\text{m-sized graphite}\)** (dotted pink line)
Results: Fit the mid-IR extinction

$R_V = 3.1$ sil.+gra/PAH+ $\mu$m-sized gra.

$A_\lambda / N_H (10^{-22} \text{ mag cm}^2)$

- $\mu$m-sized graphite
  - $a_0 = 1.2 \mu$m, $\sigma = 0.3$, C/H = 137 ppm

- sil.+gra/PAH+ $\mu$m-sized gra.
- sil.+gra/PAH

$\lambda$ (\(\mu\)m)

References:
- $R_V = 3.1$ CCM
- Wang et al. (2013)
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- Gao et al. (2009)
- Flaherty et al. (2007)
- Jiang et al. (2006)
- Indebetouw et al. (2005)
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Emission

Dusting the Universe@Tucson, AZ
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    • (Jones et al. 2013)
Summary

- μm-sized graphite grains or water ices
- a log-normal distribution
- Reproduction of the mid-IR extinction
- consistent with the observed IR/mm emission up to $\lambda \geq 2000 \, \mu m$
Dust modelling: very large grains

  Very large interstellar grains as evidenced by the mid-infrared extinction

• Wang, Li & Jiang 2015, MNRAS 454, 569
  The interstellar oxygen crisis, or where have all the oxygen atoms gone?

• Wang, Li & Jiang 2014, PSS 100, 32
  Modeling the infrared interstellar extinction
Post-Doctoral Position

https://jobregister.aas.org/node/53477

Interstellar/Circumstellar Dust

Deadline to Apply for Job: June 1, 2016
Merci Beaucoup