Low-mass Stars with Extreme Mid-Infrared Excesses: Potential Signatures of Planetary Collisions

Dissertation Defense Talk

Christopher A. Theissen
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Driving Questions

• How often do low-mass stars in the field exhibit extreme MIR excesses?

• What are the physical trends we observe for low-mass stars exhibiting extreme MIR excesses?

• Do binary systems exhibit extreme MIR excesses more often than single stars?
Star/planet formation in a nutshell

Peaks in the far-IR

Peak flux moves to shorter wavelengths

Star is now visible in the optical

Flux dominated by star, with a potential small MIR excess

Spectral Energy Distribution

< 10,000 years

~ 100,000 years

~ 1 million years

> 10 million years

André (1994)
“Extreme” MIR Excesses

Weinberger+ (2011)
“Extreme” MIR Excesses

1 billion year old binary system!

Weinberger+ (2011)
What is the interpretation?

Collisions between terrestrial planets

Credit: NASA/JPL
What is the interpretation?

Credit: S. Raymond
Seven systems currently known

HD 23514: 360 AU, 120 Myr
HD 15407: 1200 AU, 80 Myr
ID8: 35 Myr
P1121: 80 Myr
TYC-8241-2652-1: 10 Myr
BD +20 307: 1 Gyr
TYC-8830-410-1: ?
Seven systems currently known

All solar-type (FGK) stars. Why are there no low-mass stars in the sample?

- **HD 23514**: 360 AU, 120 Myr
- **HD 15407**: 1200 AU, 80 Myr
- **ID8**: 35 Myr
- **P1121**: 80 Myr
- **TYC-8241-2652-1**: 10 Myr
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- **TYC-8830-410-1**: ?

All solar-type (FGK) stars.
What exactly is a “low-mass” star?

- Less than 60% the mass of the Sun
- Cool stars (Temperatures < 4600 K)
- Red dwarfs
- M dwarfs

Credit: NASA
They have incredibly long (main sequence) lifetimes

![Graph showing the relationship between mass and lifetime. The graph indicates that stars with a mass of approximately 0.9 solar masses have a current age of the universe indicated by a red line at 10 billion years.]
They have incredibly long (main sequence) lifetimes

![Graph showing the lifetimes of stars of different masses. The x-axis represents mass in solar masses (M☉), and the y-axis represents lifetime in billion years. The current age of the Universe is indicated by a red line. The graph highlights that low-mass stars live here.](image)
~70% of all stars are low-mass stars
Low-mass Stars are Everywhere (with Earth-sized Planets!)
Planets orbit close-in

KOI-961 and Its 3 Known Planets

Jupiter and Its 4 Largest Moons

Credit: Muirhead+ (2012)/NASA
Planets orbit close-in

Credit: Gillon+ (2016, 2017)/NASA
The *Kepler* Dichotomy

*Kepler* has found lots of multi- and single-transiting planetary systems.

- Both populations cannot be explained by the same planetary architecture (Ballard & Johnson 2016).

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Multi-planet model

Multi-planet model excluding single-transiting systems

Multi-planet model with eccentricities

Ballard & Johnson (2016)
The *Kepler* Dichotomy

**Mixture model for a dual population**

<table>
<thead>
<tr>
<th>Singles</th>
<th>Multis</th>
</tr>
</thead>
<tbody>
<tr>
<td>slower stellar rotation rates</td>
<td>faster stellar rotation rates</td>
</tr>
<tr>
<td>farther from the Galactic plane</td>
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Ballard & Johnson (2016)
The *Kepler* Dichotomy

Mixture model for a dual population

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Ballard & Johnson (2016)
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Using M Dwarfs

The spectroscopic sample

The photometric sample
Building the photometric sample
Motion Verified Red Stars (MoVeRS)

1 arcminute

SDSS

SDSS + 2MASS

SDSS + WISE

Theissen+ (2016)
Building the photometric sample Motion Verified Red Stars (MoVeRS)

Theissen+ (2016)

1 arcminute

SDSS

SDSS + 2MASS

SDSS + WISE
...and the Late-Type Extension to MoVeRS (LaTE-MoVeRS)

~47,000 late-type objects with temperatures < 3800 K
...and the Late-Type Extension to MoVeRS (LaTE-MoVeRS)

Complimentary to Gaia

~47,000 late-type objects with temperatures < 3800 K
Selecting M Dwarfs with Excess MIR Flux

Multiple criteria to select stars with excess MIR flux.

Theissen & West (2014)

The photometric sample

Theissen & West (2017)
Spectral Energy Distributions for Extreme MIR Excesses

The spectroscopic sample

\[
\log [\lambda F_\lambda (\text{erg s}^{-1} \text{cm}^{-2})] = 152
\]

\[
\begin{align*}
\text{SpT} &= dM1 \\
T_* &= 3600^{+100}_{-100}\text{K} \\
T_{\text{IR}} &= 175^{+10}_{-10}\text{K}
\end{align*}
\]

The photometric sample

\[
\begin{align*}
\text{objID} &= 1237678920195637464 \\
T_* &= 3105^{+79}_{-21}\text{K} \\
T_{\text{dust}} &= 209 \pm 47\text{K}
\end{align*}
\]

Theissen & West (2014)

Theissen & West (2017)
Aging M Dwarfs: Hydrogen Emission aka "Activity"

West+ (2008)
Hydrogen Emission

Obtained DCT (and SDSS) optical spectra of randomly selected stars.

Adapted from Theissen & West (2017)
Hydrogen Emission

Stars later than M4 are inactive, indicating a field population likely older than a few billion years

Adapted from Theissen & West (2017)
Know Thy Star, Know Thy Disk

Temperatures estimates from SED fits.
Radius estimates from SED fits + distances.
Know Thy Star, Know Thy Disk

The spectroscopic sample

The photometric sample

Theissen & West (2014)

Theissen & West (2017)
Driving Questions

• How often do low-mass stars in the field exhibit extreme MIR excesses?

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Model of low-mass stars and their kinematics in our Galaxy

The Low-mass Kinematics model (LoKi)
Model of the (Nearby) Galaxy

Model of low-mass stars and their kinematics in our Galaxy

The Low-mass Kinematics model (LoKi)

Available on GitHub!
What percentage of low-mass field stars exhibit extreme MIR excesses?

\[ \sim 0.04\% \text{ of low-mass stars exhibit extreme MIR excesses} \]
What percentage of low-mass field stars exhibit extreme MIR excesses?

~0.04% of low-mass stars exhibit extreme MIR excesses as compared to 0.0007% of solar-type stars (AFGK-spectral types)
Driving Questions

• How often do low-mass stars in the field exhibit extreme MIR excesses?

• What are the physical trends we observe for low-mass stars exhibiting extreme MIR excesses?

• Do binary systems exhibit extreme MIR excesses more often than single stars?
Is there a mass trend?

There might be a slight trend with stellar mass, indicating lower-mass stars are more likely to host an extreme MIR excess.
Is there an age trend?

Stars further away from the Galactic plane are, on average, older.
Is there an age trend?

Stars further away from the Galactic plane are, on average, older.
Is there an age trend?

The spectroscopic sample

The photometric sample

Fraction = \( \frac{\text{# stars w/ MIR excess}}{\text{Total # stars}} \)

Theissen & West (2014)

Theissen & West (2017)
Is there an age trend?

Theissen & West (2014)

The spectroscopic sample

The photometric sample

Fraction = \frac{\text{# stars w/ MIR excess}}{\text{Total # stars}}
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- TYC-8830-410-1: ?
White Dwarf + M Dwarf Binaries (WD+dM)

Similar luminosity binaries, but with different peaks in their spectral energy distributions.

Can be detected with low- to moderate-resolution spectra.

Morgan+ (2012)
Two Binaries Found

Theissen+ in prep.
Two Binaries Found
Plus One

Debes+ (2012)
What percentage of WD+dM systems exhibit extreme MIR excesses?

~0.04% of WD+dM systems exhibit extreme MIR excesses
What percentage of WD+dM systems exhibit extreme MIR excesses?

~0.04% of WD+dM systems exhibit extreme MIR excesses

These are small number statistics with no way to account for completeness yet. More work is needed.
Conclusions

- How often do low-mass stars in the field exhibit extreme excess MIR flux?
  - Approximately 0.04% of low-mass field stars exhibit extreme MIR excesses (versus 0.0007% for solar-type stars).

- What are the trends we observe for low-mass stars exhibiting extreme MIR excesses?
  - An age trend is observed, with younger field stars exhibiting a higher incidence of extreme MIR excesses over older field populations.
  - There may be a mass dependence, with lower-mass stars more likely to exhibit an extreme MIR excess.

- Do binary systems exhibit extreme MIR excess more often than single stars?
  - Using WD+dM systems, I find binaries typically host dust as often as single stars. Origins may be vastly different though.
Acknowledgements

(No one does it alone)
Aging SDSS M Dwarfs I: Surface Gravity

Theissen & West (2014)
Aging SDSS M Dwarfs II: Hydrogen emission

Morgan et al. (2012)
Aging SDSS M Dwarfs II: Hydrogen emission

Theissen & West (2014)
Building the Photometric Sample
Motion Verified Red Stars (MoVeRS)

Theissen+ (2016)
Using MoVeRS: Defining the Sample

Theissen & West (2017)
Contamination Rate?
Giants versus Dwarfs

Candidate stars tend to follow the dwarf population.

~4% contamination
6th Order Polynomial
Dartmouth ([Fe/H] = 0) 5 Gyr
Dartmouth ([Fe/H] = 0) 10 Gyr
Dartmouth ([Fe/H] = -2.4) 10 Gyr
Mann et al. 2015

This study
Mann et al. 2015
Boyajian et al. 2012

Theissen & West (2017)
Youth Tracers Part Deux

Obtained SDSS and DCT optical spectra of randomly selected stars.

Stars are again consistent with the field population.
Model of the (Nearby) Galaxy

Model of the low-mass stars and their kinematics in our Galaxy

The Low-mass Kinematics model (LoKi)

Theissen & West (2017)
Model of the (Nearby) Galaxy

Available on GitHub!

Model of the low-mass stars and their kinematics in our Galaxy

The Low-mass Kinematics model (LoKi)

Theissen & West (2017)
Is There an Age Effect?

Adapted from West et al. (2011)

Galactic Stratigraphy
What are the trends with MIR excesses?

Younger field stars are more likely to host an extreme MIR excess.

There might be a slight trend with stellar mass, indicating lower-mass stars are more likely to host an extreme MIR excess.

Theissen & West (2017)
What are the trends with MIR excesses?

Theissen & West (2017)
Locating Binaries

Very tight binaries require high-resolution spectroscopy (over multiple epochs) to find.
Locating Binaries

Intermediate separation binaries require high-resolution adaptive optics imaging

(i) SDSS J2052-1609 \( K_s \).

Bardalez-Gagliuffi+ (2015)
Current Samples with MIR Excesses

Using available samples, selected WD+dM systems with excess MIR flux

Theissen+ in prep.
A Tool for Measuring *WISE* Source Quality

A tool to measure source “roundness” and band-to-band correlation.

The unWISE Intrinsic Source Estimator for Sureness and Trustworthiness (*unWISEST*)

Theissen+ in prep.
A Tool for Measuring WISE Source Quality

A tool to measure source “roundness” and band-to-band correlation.

Available on GitHub!

The unWISE Intrinsic Source Estimator for Sureness and Trustworthiness (unWISEST)

Theissen+ in prep.
Circumbinary Dust

Dust orbits both components of the binary

Farihi+ (2017)
WD+dMs with Dust

These are all interacting binaries

Hoard (2013)