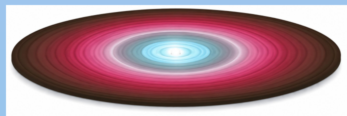
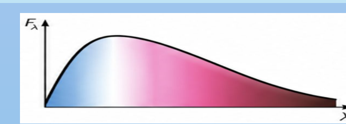
# Quantitative Spectroscopic Diagnostics for FU Ori Disks




Evan Portnoi, Lynne Hillenbrand, Adolfo Carvalho

California Institute of Technology and Harvard-Smithsonian CfA


## Introduction and Summary

We present near-infrared spectroscopic diagnostics that can be used to identify and characterize FU Orionis disks. Considering both the spectra predicted by pure-accretion disk atmosphere models, and existing literature, we identify key diagnostic features of FUOrs in YJHK– **see upper Figure**.

Some of the chosen features are proxies for temperature, others are sensitive to surface gravity, and still others probe disk winds. We compare measurements – **see middle Figure -** between new Palomar spectra of 28 FUOrs with those from a control sample of late-type dwarfs and evolved stars from the IRTF Spectral Library. A number of parameter spaces that can distinguish FUOr disks from normal stars are identified – **see lower Figure.**

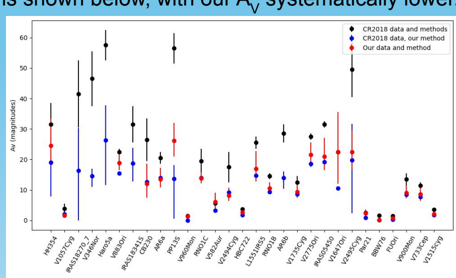
## The Median FUOr Spectrum

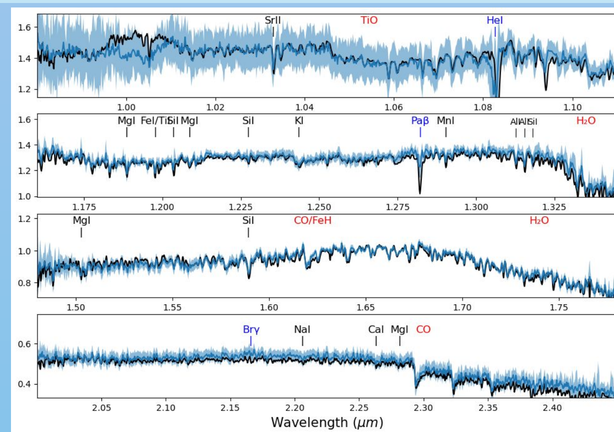
We construct the median spectrum of an outbursting FUOr disk (**upper Figure**) as follows.

As a reference for dereddening, we adopt a fiducial gas disk model with the parameters used to fit FU Ori itself, as described in Carvalho et al. (2025), with $T_{max}$ = 5900 K. Each observed spectrum is dereddened to the color of the fiducial FUOr disk model.

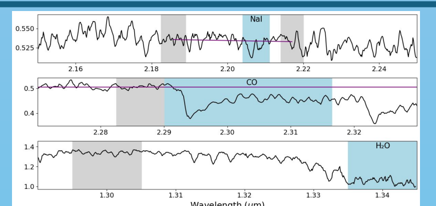
1) The observed spectrum is normalized at 1.67 μm.
2) Only the spectral range 0.98-1.78 μm is considered, ignoring the K Band (2.0-2.45 μm) due to thermal emission from the outer dust disk that is not represented in the model.
3) Finally, we apply observed extinction curves over the range $A_V$ = 0 to $A_V$ = 40, and find the lowest reduced $\chi^2$.

Comparison of our $A_V$ values with Connelley & Reipurth (2018) is shown below, with our $A_V$ systematically lower.

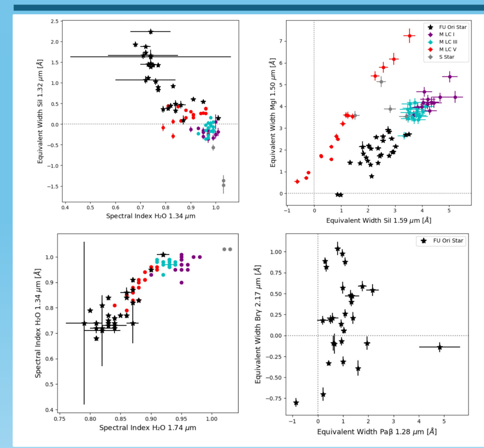



Panels show the YJHK near-infrared bands and the median flux after dereddening for our sample of 28 FUOrs (blue line). The mean absolute deviation is the shaded region, with increased scatter towards shorter wavelengths due to reduced SNR for high $A_V$. The spectrum of FU Ori itself is plotted in black, *demonstrating how well the prototype represents the population (!!)*. Measured spectral features are labeled, with molecules in red, atoms in black, and wind-sensitive lines shown in blue.




Feature strength methods illustrated using the median FUOr (**upper Figure**). Top panel shows a standard equivalent width measurement, for Na I. Middle panel shows an equivalent width with only one continuum region on the blue side, using CO. Bottom panel shows an index ratio, using $H_2O$.




## Measuring FUOr Spectral Features

We measure spectral indices **(middle Figure)** for each object in our sample. Three measurement methods are employed**.**

**Equivalent Width.** This method is used for standard Gaussian lines where integration across the feature is appropriate. In the top panel, blue shading represents the integration limits and gray shading represents continuum on either side of the feature. Purple line is estimated continuum.

**One-Sided Equivalent Width.** This method is used only for the K-band CO bandhead region where there is no red-side continuum. In the middle panel we measure continuum on the blue side, and assume it is flat across the feature, as indicated by the purple line.

**Spectral index.** This method is used for $H_2O$ and TiO, as these are broad, non-Gaussian molecular features. Feature strength is measured (lower panel) by taking a ratio of the gray continuum and the blue feature.

## Results

Several spectroscopic parameter spaces are identified as effective diagnostics of an FUOr disk. We compare (**lower Figure**) the measured FUOr feature strengths (black) with M dwarfs (red), M giants (cyan), and M supergiants (purple).

In the **top left plot** within J-band, molecular $H_2O$ at 1.34 μm is shown relative to atomic SiI at 1.32 μm. A similarly useful plot in the K-band is CO vs CaI or CO vs NaI (more-so than the standard CO vs CaI+NaI). The FUOr population is distinct.

In the **top right plot** within H-band, both atomic SiI at 1.59 μm and MgI at 1.50 μm are temperature sensitive, as well as gravity-sensitive. There is a clear temperature gradient within the M-dwarf population, with the giant populations separated. The FUOr population is distinct.

In the **bottom left plot**, the J-band and H-band (1.78 μm) $H_2O$ feature strengths are shown. The FUOr population is distinct, exhibiting stronger $H_2O$ than even the M-dwarfs.

In the **bottom right plot**, showing wind line equivalent widths, FUOrs typically have Paβ absorption with weak/absent Br**γ**.