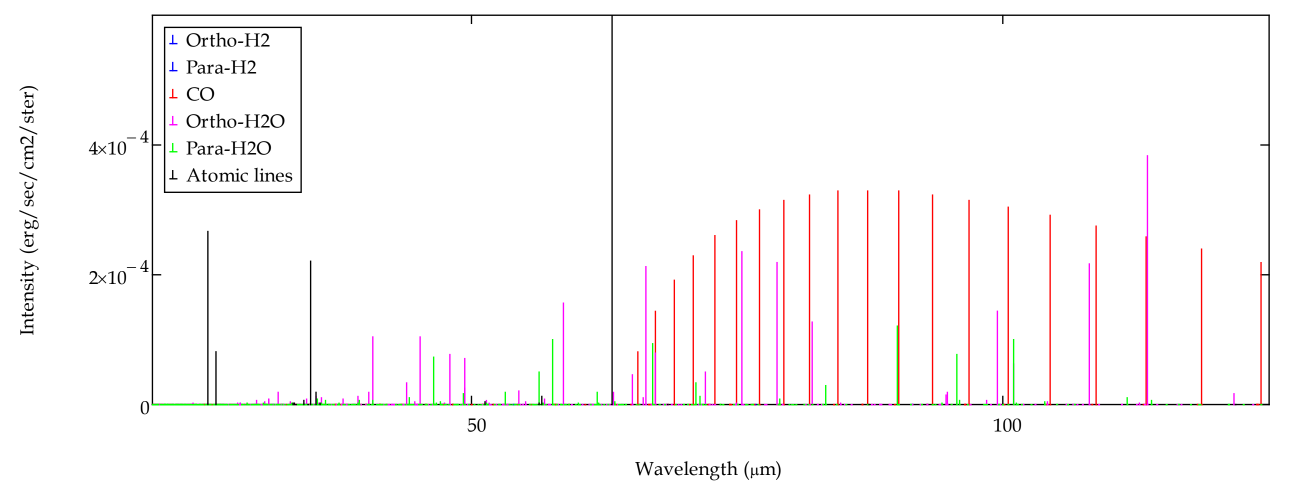
Outflows and the shocks they drive

Star-formation feedback from outflows in Galactic young stellar objects, and the HIRMES opportunity.



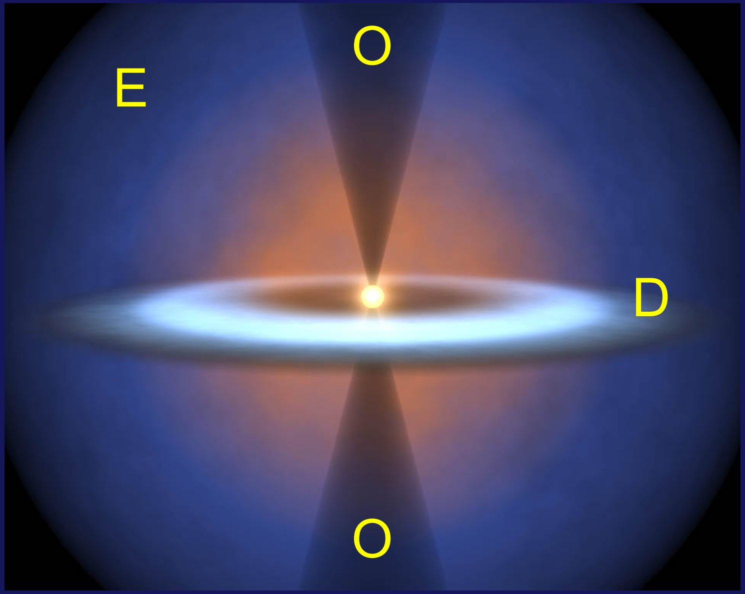
Dan Watson

For the SOFIA HIRMES Instrument Team

SOFIA tele-talk 2-12-2020

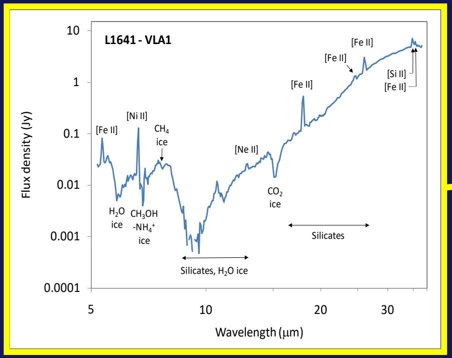
Characterization of star formation requires characterization of the flows around protostars.

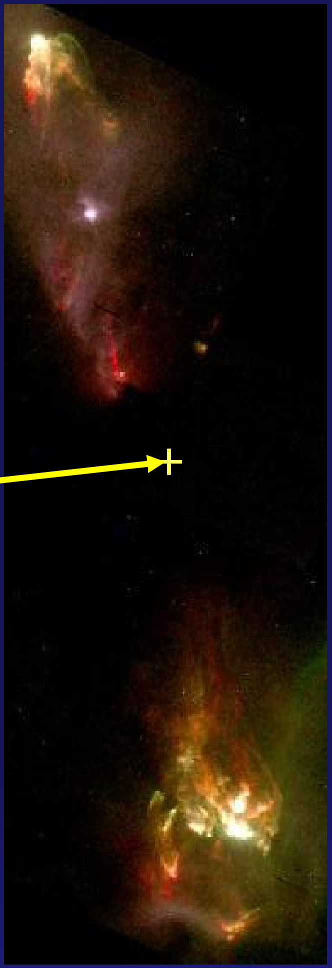
- ☐ Stars and protoplanetary disks form from inside-out collapse of molecular cloud envelopes.
- ☐ Envelope material (E) continues to rain onto disk (D); disk material accretes onto star.
- ☐ Angular momentum shed by "viscous" transport within disk, and by magnetocentrifugally-driven outflows.
- ☐ Feedback:
  - Outflow (O) deposits energy and momentum in envelope and surroundings, perhaps disrupting envelope and molecular cloud.
  - Disruption of envelope ends formation of star, determines final value of stellar mass.
  - Disruption of cloud ends star-cluster formation in region.



In turn, celestial flows are often best characterized *via* the shocks that they drive.

- ❑ Flows in and around protostars are highly supersonic.
- ❑ Interaction between flows thus takes the form of shocks.
- ❑ The shock emission can be observed much more easily than quiescent gas, and used to derive the physical parameters of the flows.
    - Images of the shocks are records of recent protostellar accretion history.
- ❑ Protostars are heavily obscured by dust extinction; must be observed at long (infrared) wavelengths.
- ❑ The mid-infrared spectrum contains the spectral lines most useful for diagnostics.



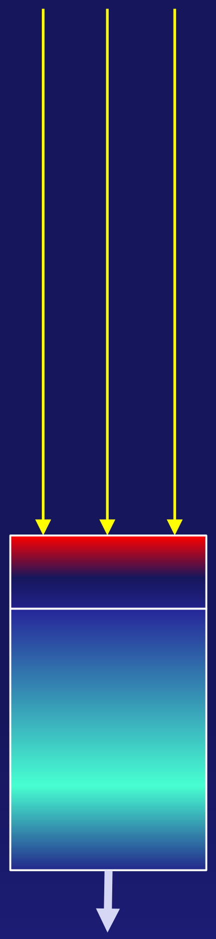


HH 1-2
Hester 1997

Shocks in the interstellar medium are commonly double.

Example of outflow-driven shocks in envelopes or ambient:

- The outflow itself (“wind”), typically with speed 40-100 km/sec, decelerates in a shock strong enough to dissociate molecules and ionize atoms collisionally.
  - Thus a shock mostly ruled by hydrodynamics, and called a *J*- (jump) type shock.
  - May have substantial radiative and/or magnetic precursors.
- The envelope or ambient material, initially cold and very low ionization, is accelerated to more modest speeds (10-40 km/sec) incapable of collisional dissociation.
  - The structure of such shocks is dominated by magnetic effects, does not exhibit a Rankine-Hugoniot jump, and is called a *C*- (continuous) type shock.



Outflow from protostar

J-shock: decelerating wind

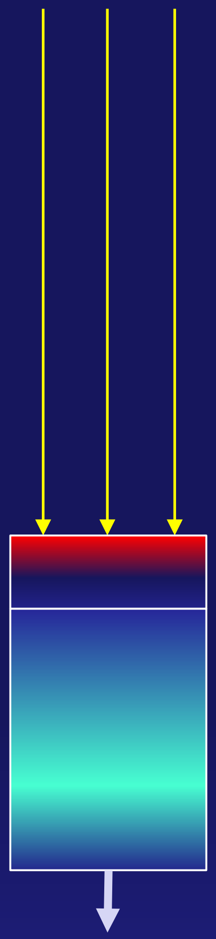
Contact discon-tinuity

C-shock: accelerating cloud material

Shocks in astrophysics are commonly double (continued).

Radiation from the shocks:

- ☐ Molecular lines: e.g. pure rotational H_2, HD, H_2O, OH, CO.
  - These lines are the dominant coolant in cloud shocks.
    - Yield T and mechanical-energy injection rates.
  - Useful abundance ratios too, particularly HD/H_2.
- ☐ Atomic fine structure lines, primarily from low-ionization species: e.g. [O I], [S I], [Si II], [Fe II], [N II].
  - Lower-ionization species are dominant coolants in the parts of the post-*J*-shock where $T < 5000$ K.
  - Higher ionization states in faster shocks: lines of [Ne II], [S III], [O III], [N III] become prominent.



Outflow from protostar

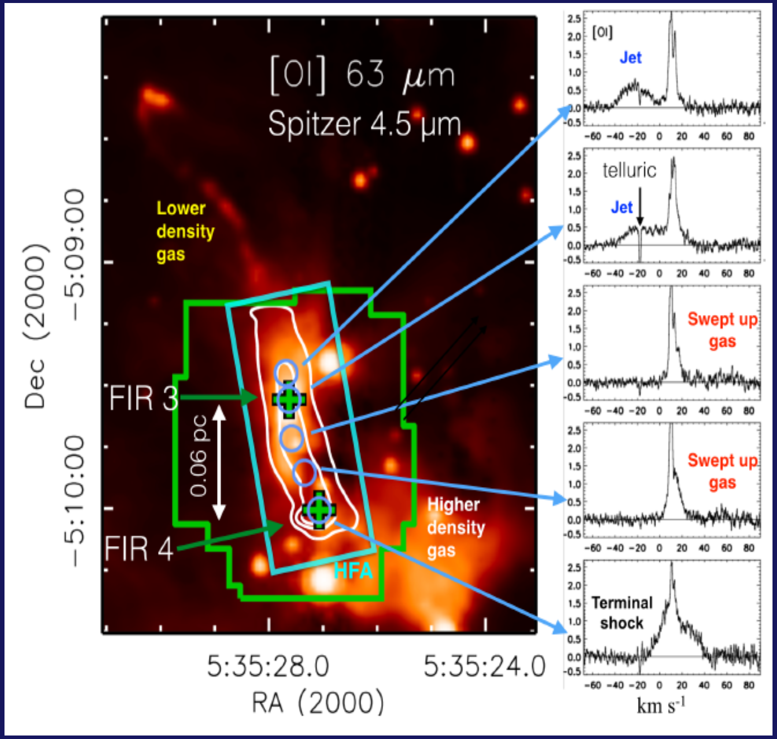
J-shock: decelerating wind

Contact discon-tinuity

C-shock: accelerating cloud material

HIRMES will have high impact in the domain of young-stellar-object outflows and star-formation feedback.

- The HIRMES band covers many of the best probes of both *J*-type and *C*-type shocks, unextinguished or not.
- HIRMES can observe these lines with an unprecedentedly combination of high sensitivity and spectral resolution.
  - HIRMES is more sensitive per pixel than GREAT, primarily due to quantum noise in coherent detection by GREAT.
  - HIRMES spectral resolution and scan coverage is more than sufficient to resolve outflow line profiles.
  - And HIRMES has many more pixels than GREAT.
- Outflows in nearby clouds are quite bright by HIRMES standards, enabling both surveys and detailed imaging of parsec-length objects.

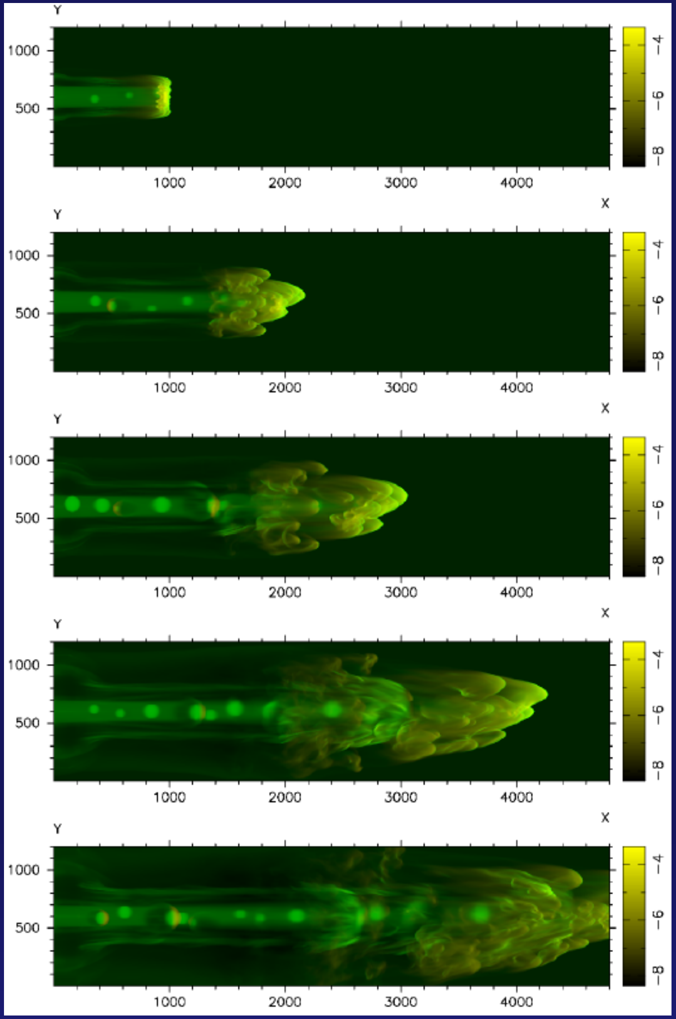


OMC-3 FIR3 outflow, observed with Spitzer-IRAC, Herschel PACS and SOFIA-GREAT (Megeath+ 2020).

Several advanced modelling tools are accessible to the community, to assist in the impact.

Thus we can be more sure than usual, that HIRMES observations will be exploited in detail.

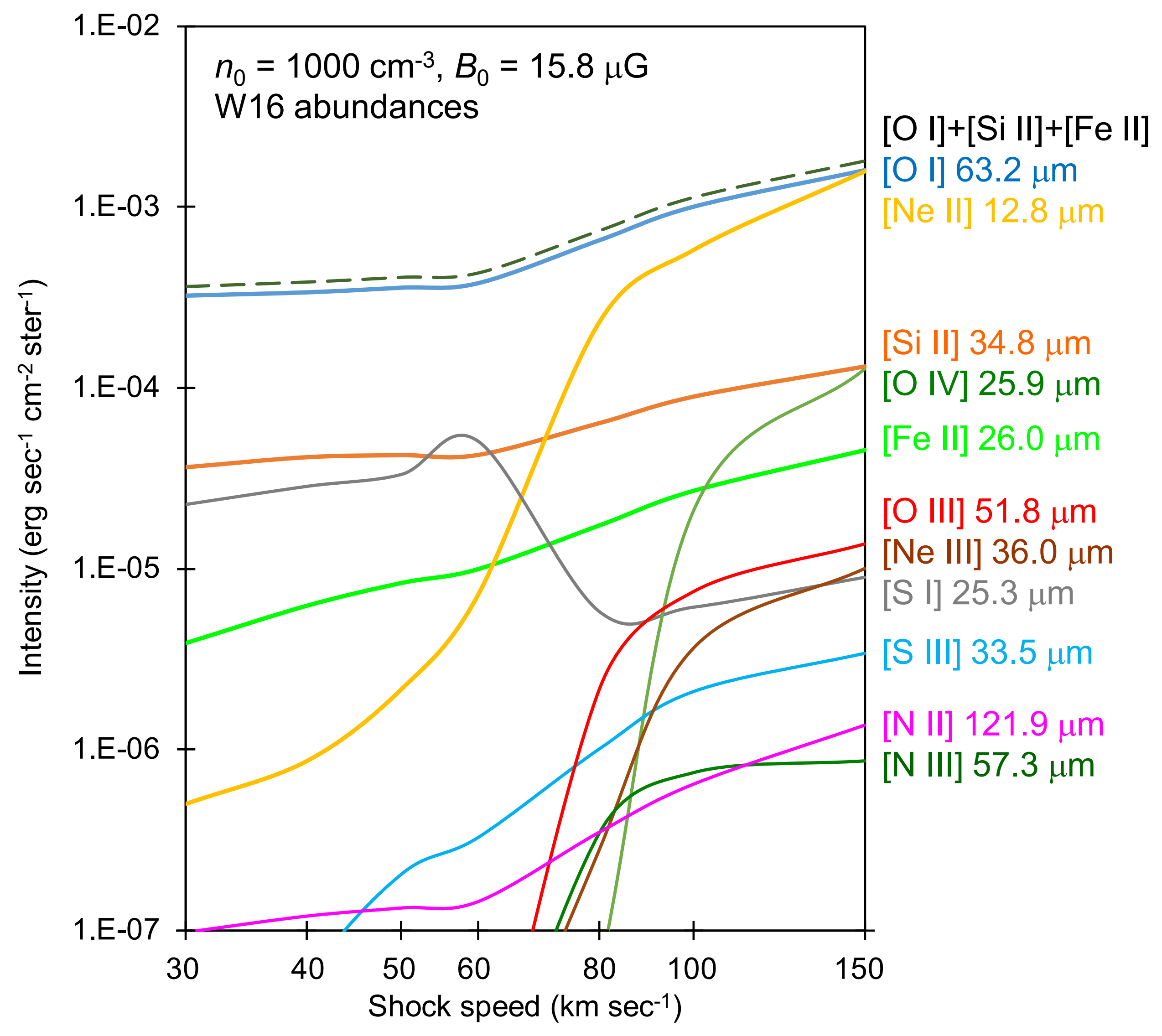
- ☐ 1-D *J* shocks: MAPPINGS V (Dopita & Sutherland 2017).
  - Now uses the CHIANTI atomic database for its cooling data.
- ☐ 1-D *C* shocks: second- and third-generation codes by Neufeld & Kaufman (e.g. 1996), and by Flower & Pineau des Forets (e.g. 2000).
  - Both use BASECOL collection of molecular collisional excitation data.
  - Beware of degeneracies.
- ☐ 3-D adaptive-mesh-refined MHD code: AstroBEAR (e.g. Carroll+ 2012).



Synthetic emission-line images of outflow-driven shocks from AstroBEAR (Yirak+2013).

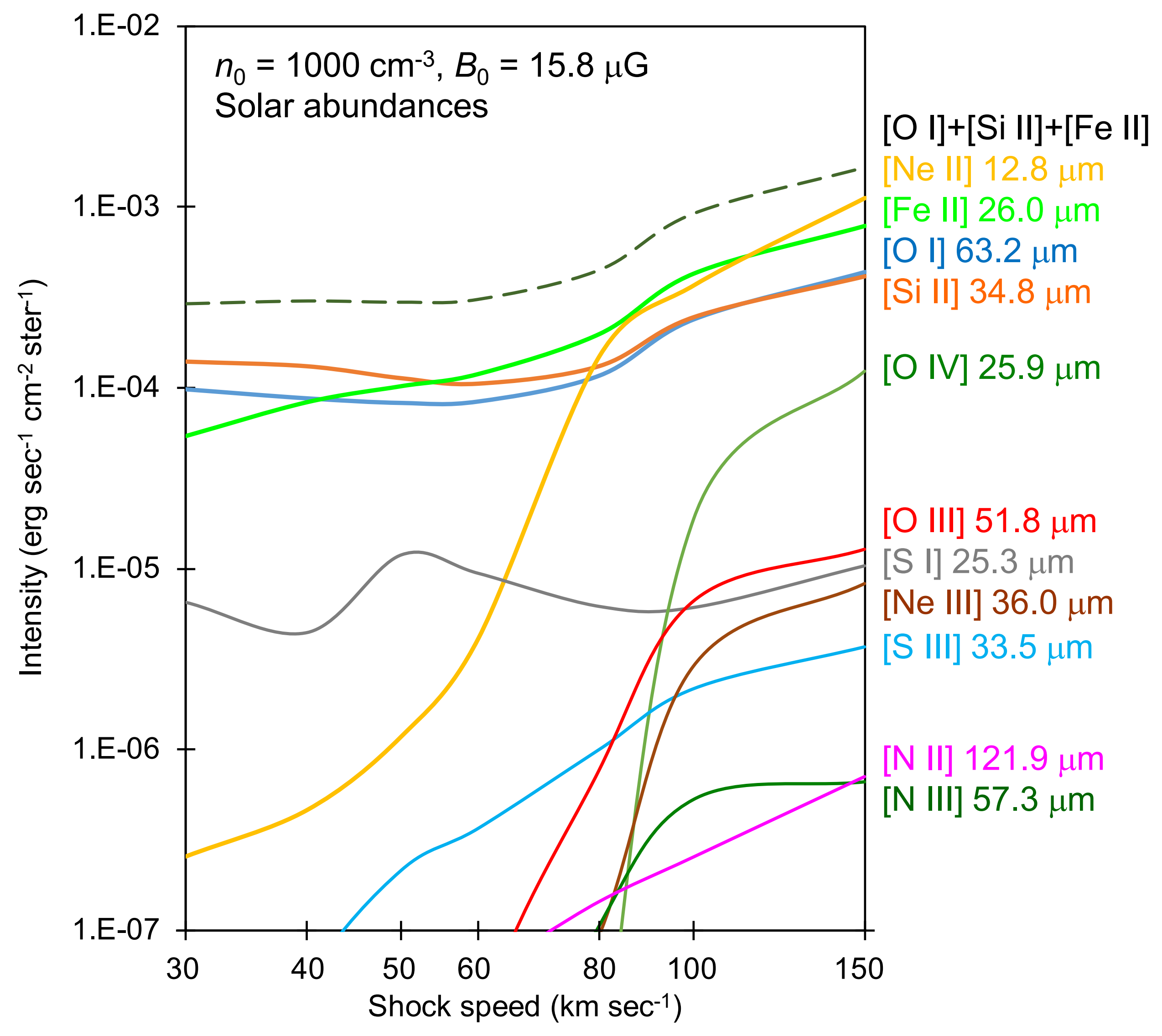
Several advanced modelling tools are accessible to the community, to assist in the impact (continued).

Calculation with MAPPINGS V.



Several advanced modelling tools are accessible to the community, to assist in the impact (continued).

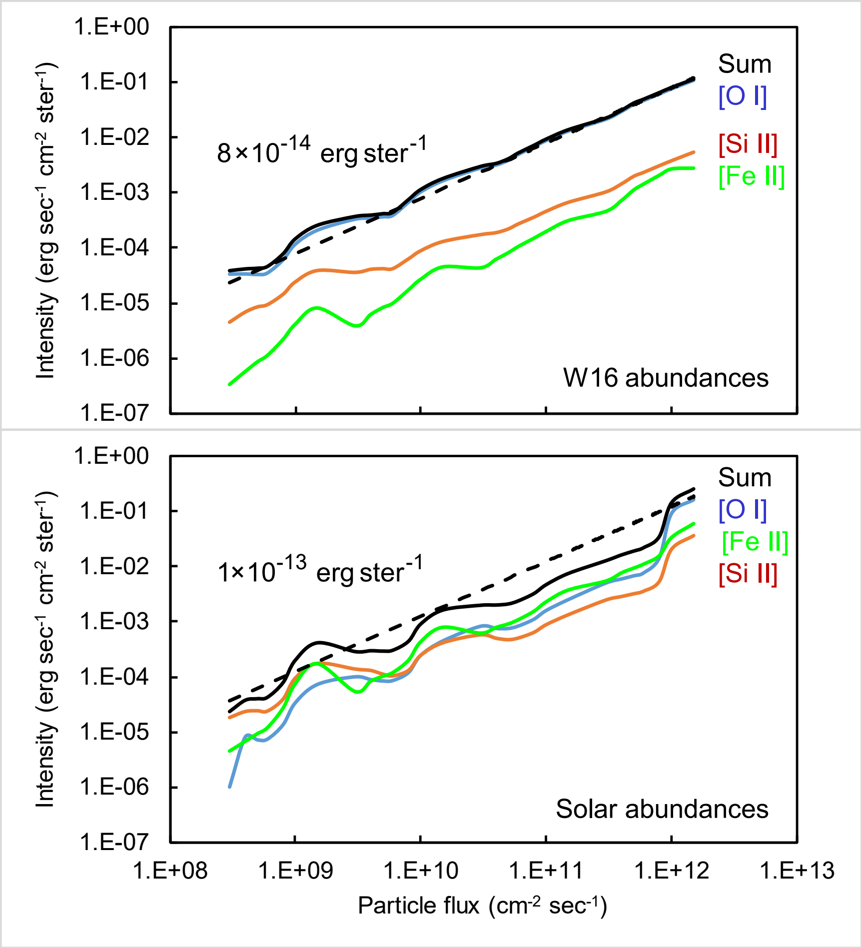
Calculation with MAPPINGS V.



But high-impact results can also be obtained in model-independent fashion.

Because the HIRMES band contains single lines, or small sets of them, that are the major coolants of their shock domain…

- flow rates can be measured "bolometrically," from integrated line intensity…
  - Like mass-flow rate, using [O I] 63.2 μm (Hollenbach 1985, Hollenbach & McKee 1989; also Watson+ 2016, Dionatos & Güdel 2016).
  - And kinetic-energy-injection rate, using H_2 or CO lines (e.g. Kaufman & Neufeld 1996, Maret+ 2009, Nisini+ 2015).
- and HIRMES can do this with spatially and spectrally resolved images, making complete accounts of the rates of mass, momentum, and energy ejection by young stellar objects.

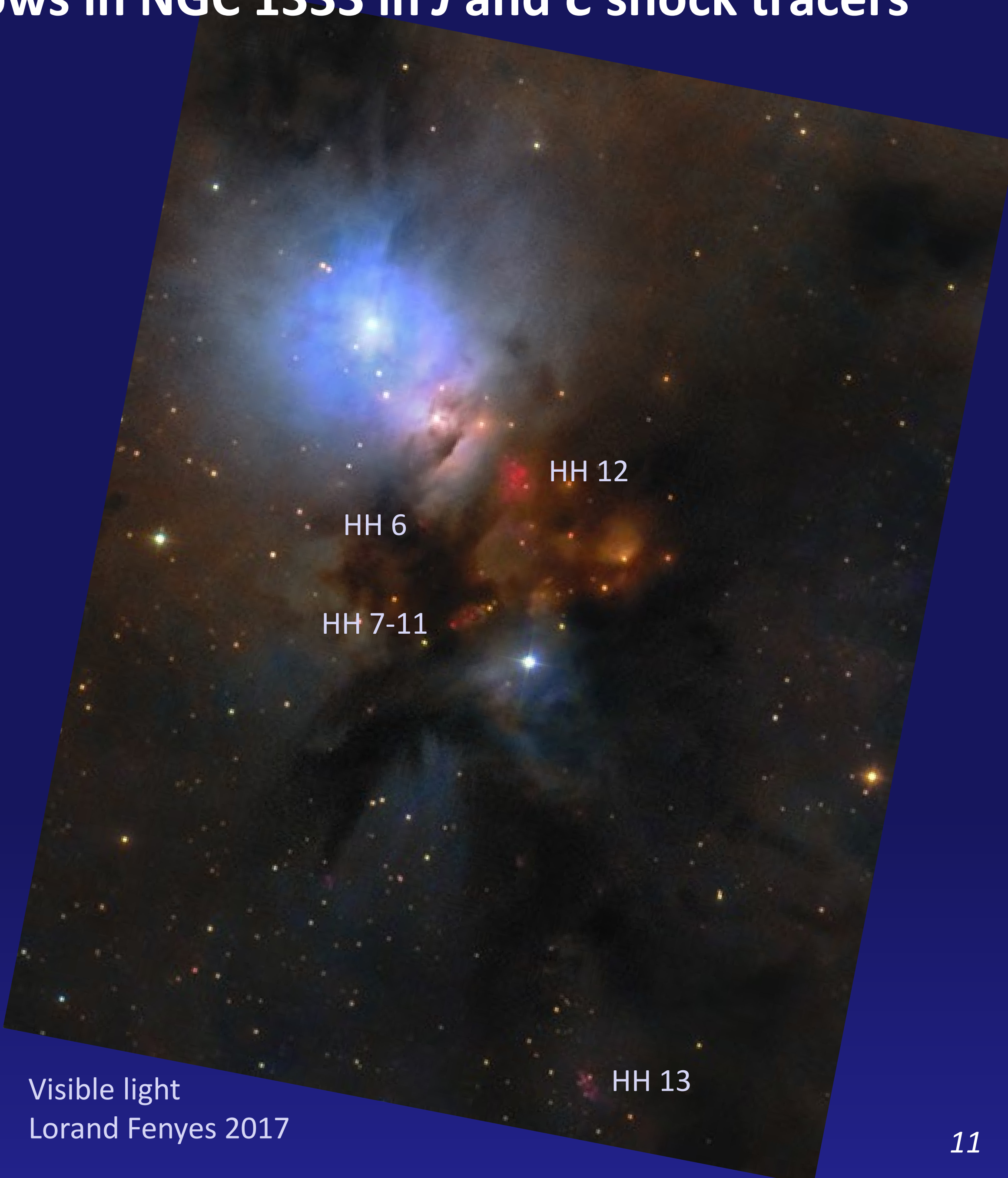


Redo of the Hollenbach (1985) result, using MAPPINGS V and up-to-date atomic physics. (The difference from that result is insignificant.)

Example: protostellar outflows in NGC 1333 in *J* and *C* shock tracers

North up, east left, common scale for the next set of images.

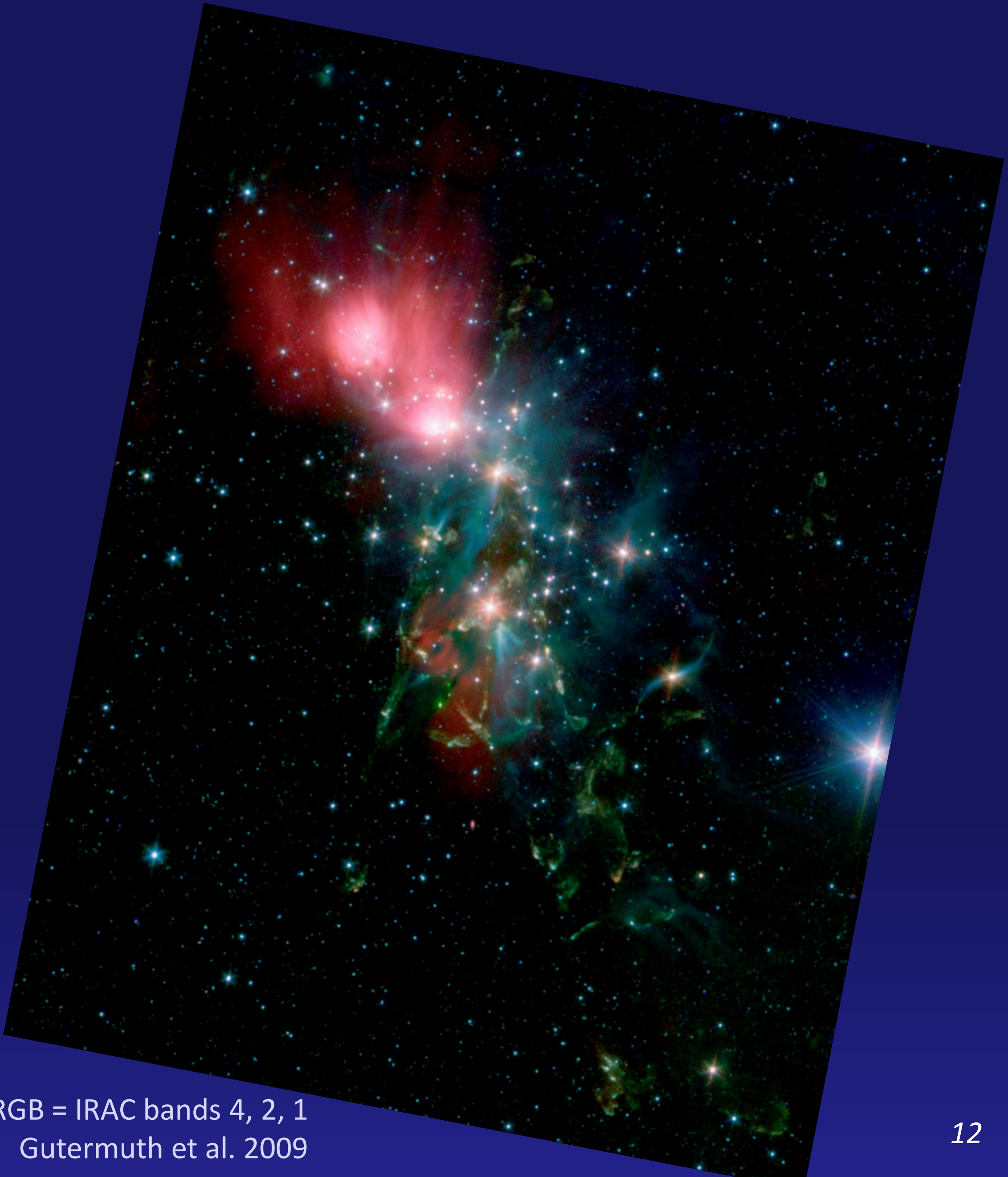
- ☐ NGC 1333 itself is the reflection nebulosity at upper left, energized by a young A0-B8 star.
- ☐ Several low-serial-number HH objects show up in red.



Visible light
Lorand Fenyes 2017

NGC 1333 (continued)

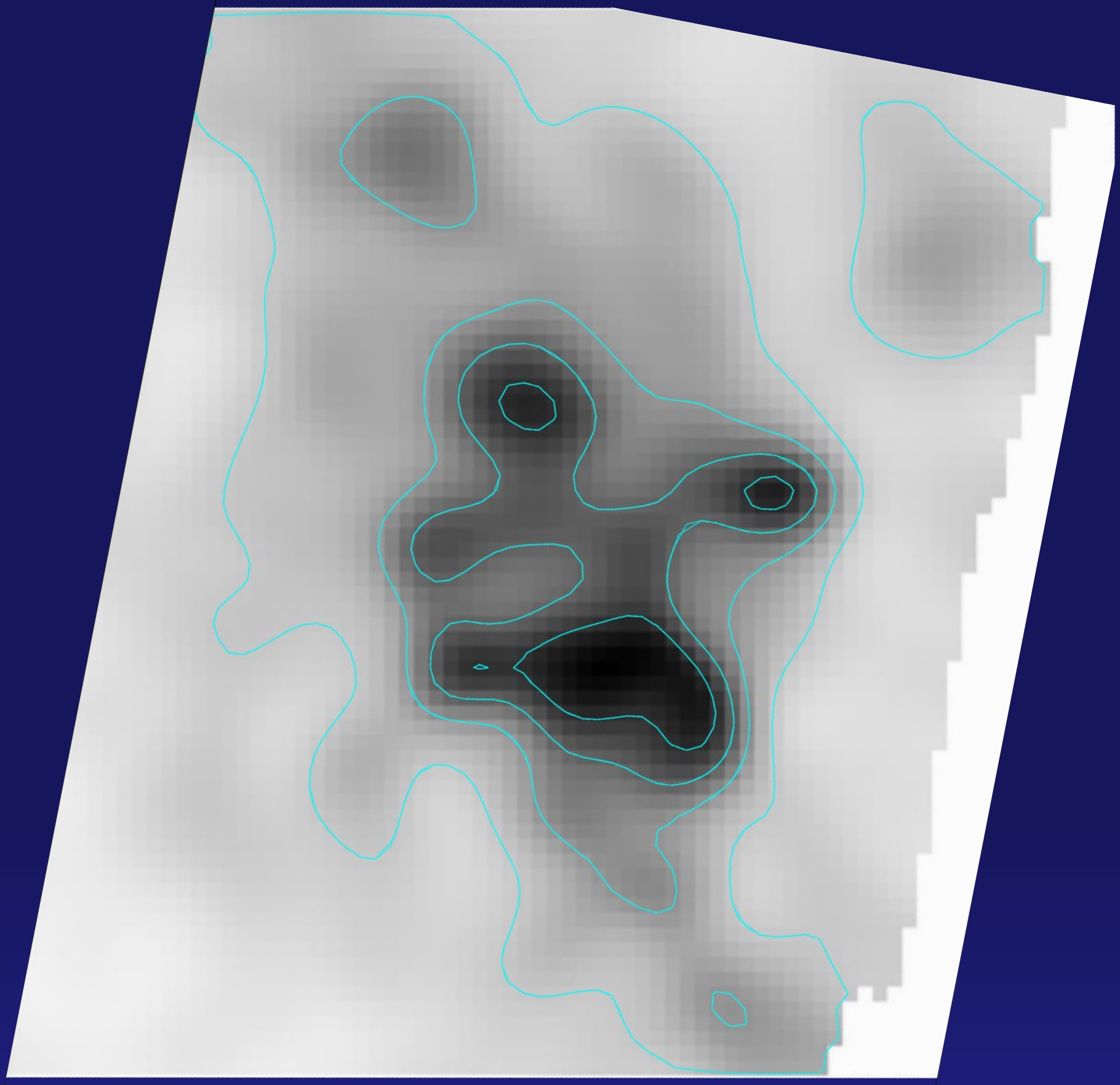
- ☐ Rob Gutermuth's famous Spitzer image shows most of the YSOs.
    - Rest found in Rob's Spitzer-MIPS 24 image.
- ☐ 40 of them – about a third – rank as Class 0 or I.
    - One of the very youngest stellar populations known.



RGB = IRAC bands 4, 2, 1
Gutermuth et al. 2009

NGC 1333 (continued)

- ☐ Get total extinction through the cloud from near-IR excesses of background stars, mostly K giants.
- ☐ This gives an accurate mass of the NGC 1333 molecular cloud: **350 $M_\odot$**.

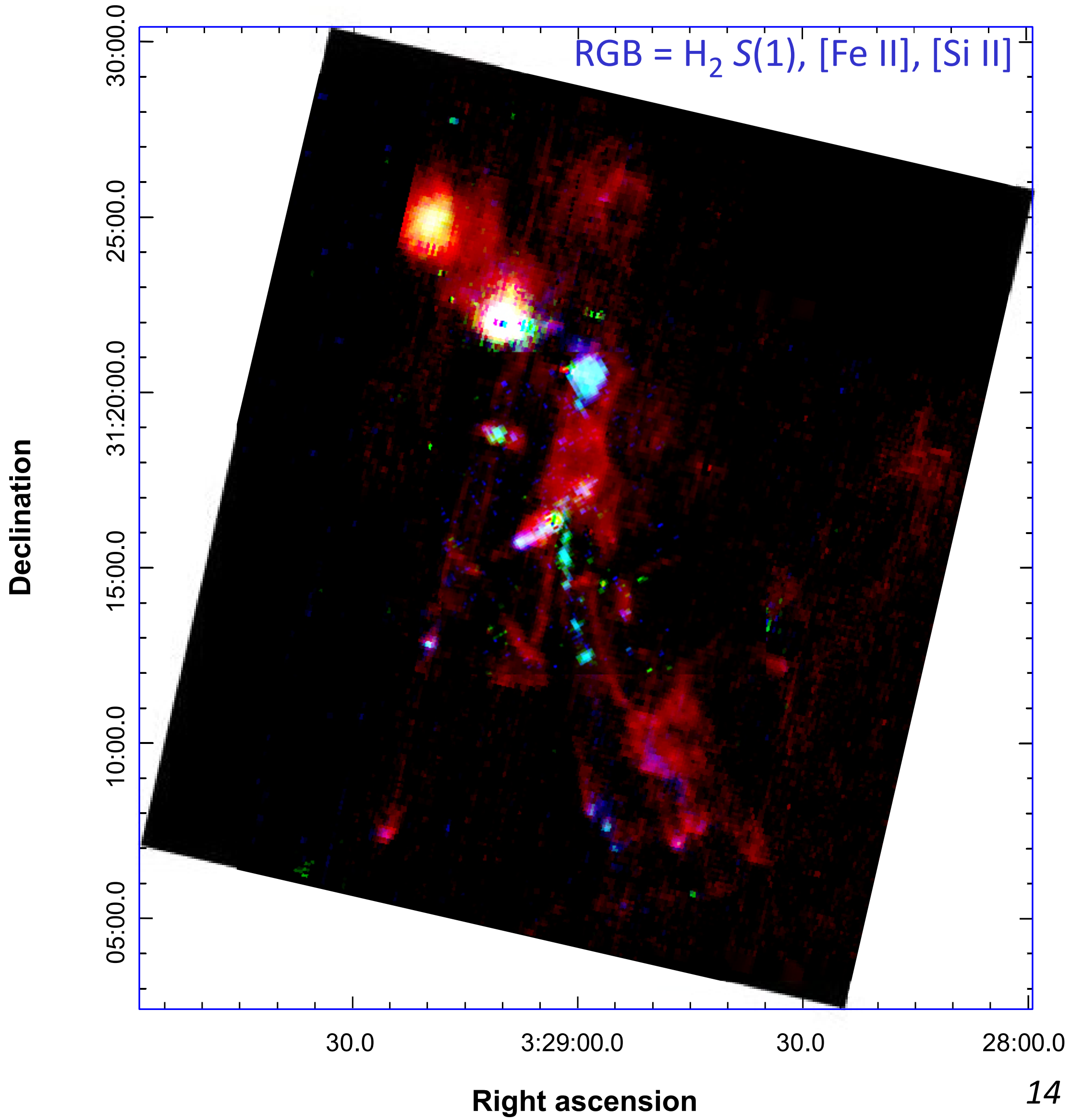


Total A_V toward background stars
Gutermuth et al. 2009

NGC 1333 (continued)

- ☐ Spitzer-IRS spectral mapping in H_2, [Fe II], [Si II].
- ☐ With HIRMES one could map regions like this in CO, and in the same *J*-shock tracers as this…
- ☐ but add kinematic information through HIRMES' high velocity resolution, which could not be obtained from a facility besides SOFIA.

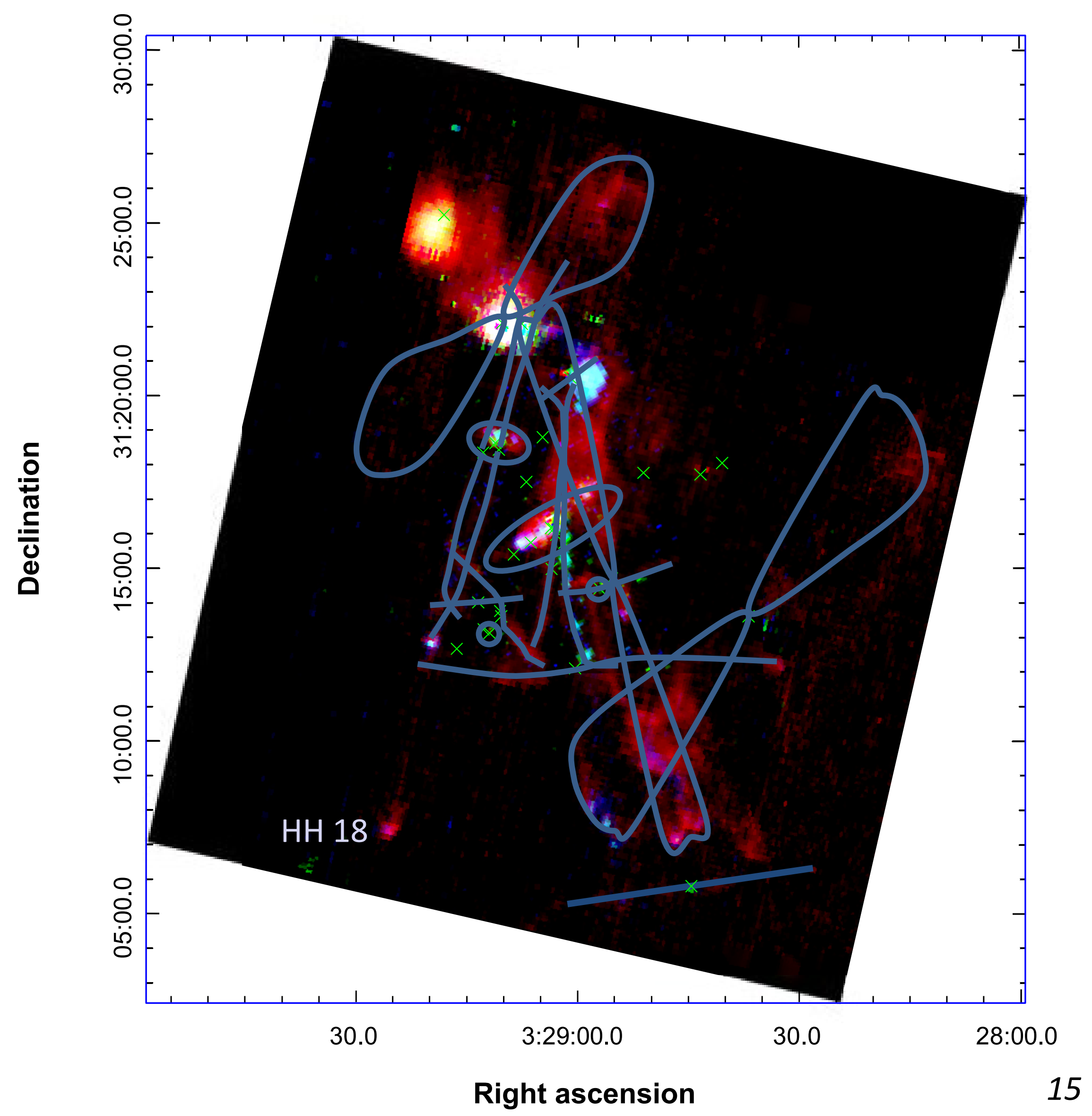
So instead of H_2 in these images, imagine HIRMES imaging CO. This, and the [Fe II] and [Si II] lines, are **all within HIRMES's grasp.**



NGC 1333 (continued)

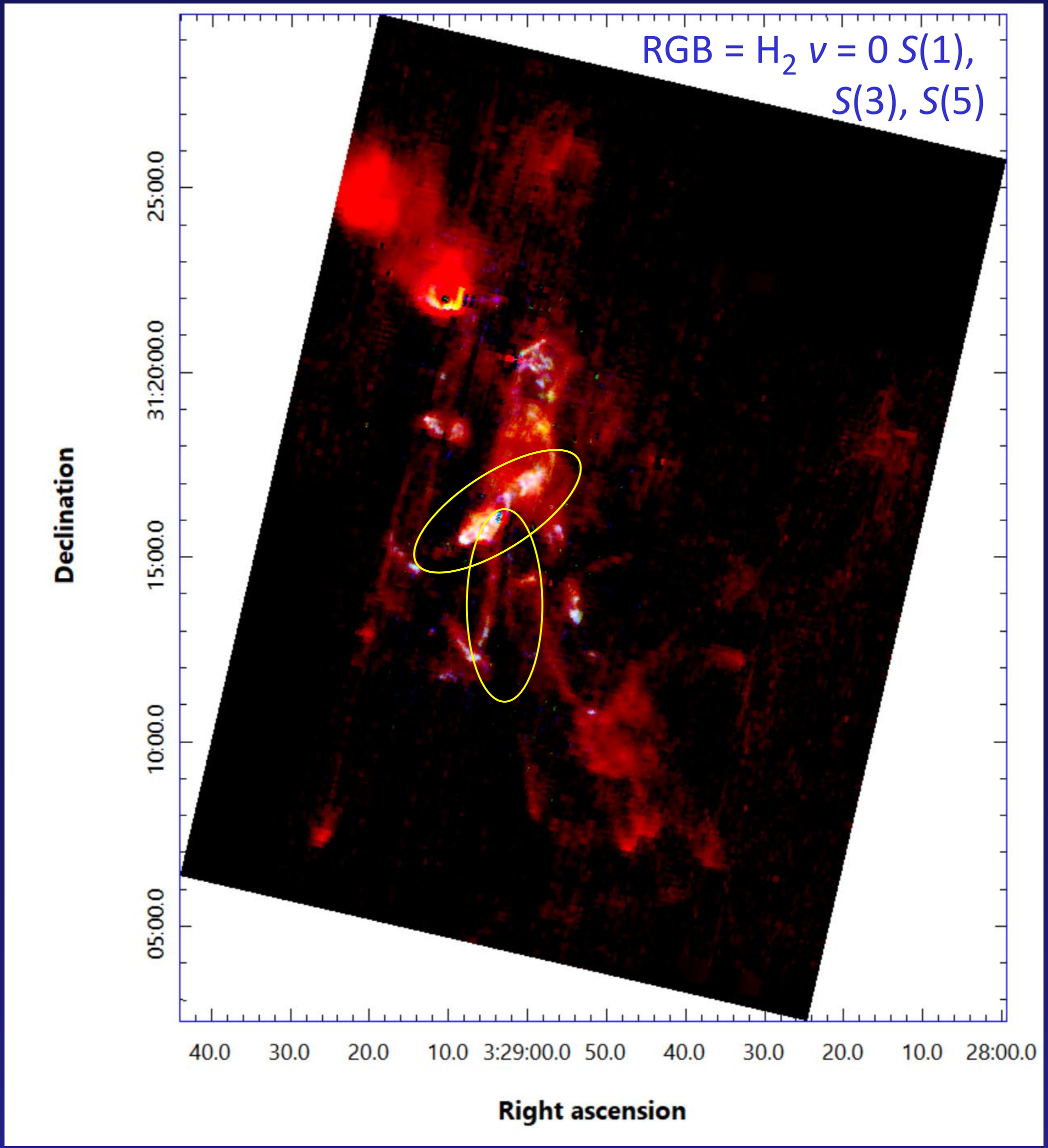
☐ **17 outflows from identified protostars.**

- 18 if you count HH 18, for which we haven't identified the outflow source.
- More than any other star formation region we know of…
- despite being 100-1000 times smaller than some we know, like the Orion giant molecular cloud.

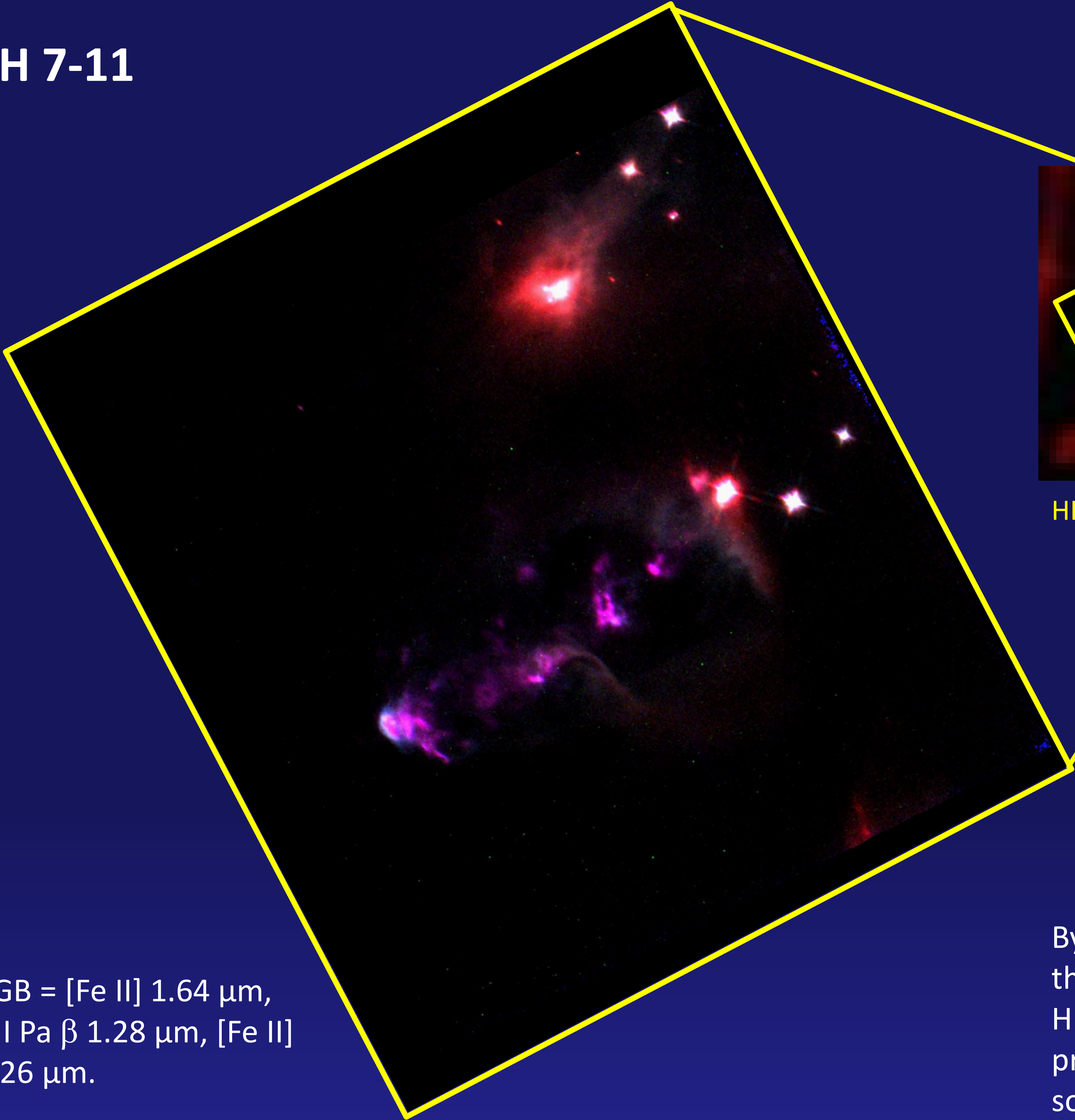


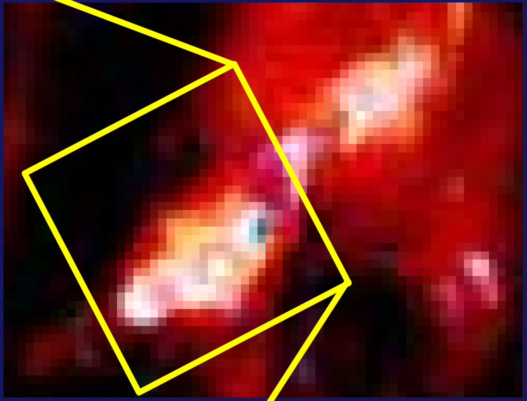
NGC 1333 (continued)

- ☐ Zoom in on the most vigorous of the outflows: the one represented by HH 7-11.
- ☐ With HIRMES, this region could be imaged in
  - [Si II] and [O I] at medium spectral resolution with S/N better than 100 on the brightest spots;
  - [O I] in high velocity resolution (3 km/sec), emphasizing the brighter HH objects, with peak S/N at least 50 in the profiles of the brightest spots;
  - all in 15 hours plus calibration time.



HH 7-11





HH 6.9

RGB = [Fe II] 1.64 μm, H I Pa β 1.28 μm, [Fe II] 1.26 μm.

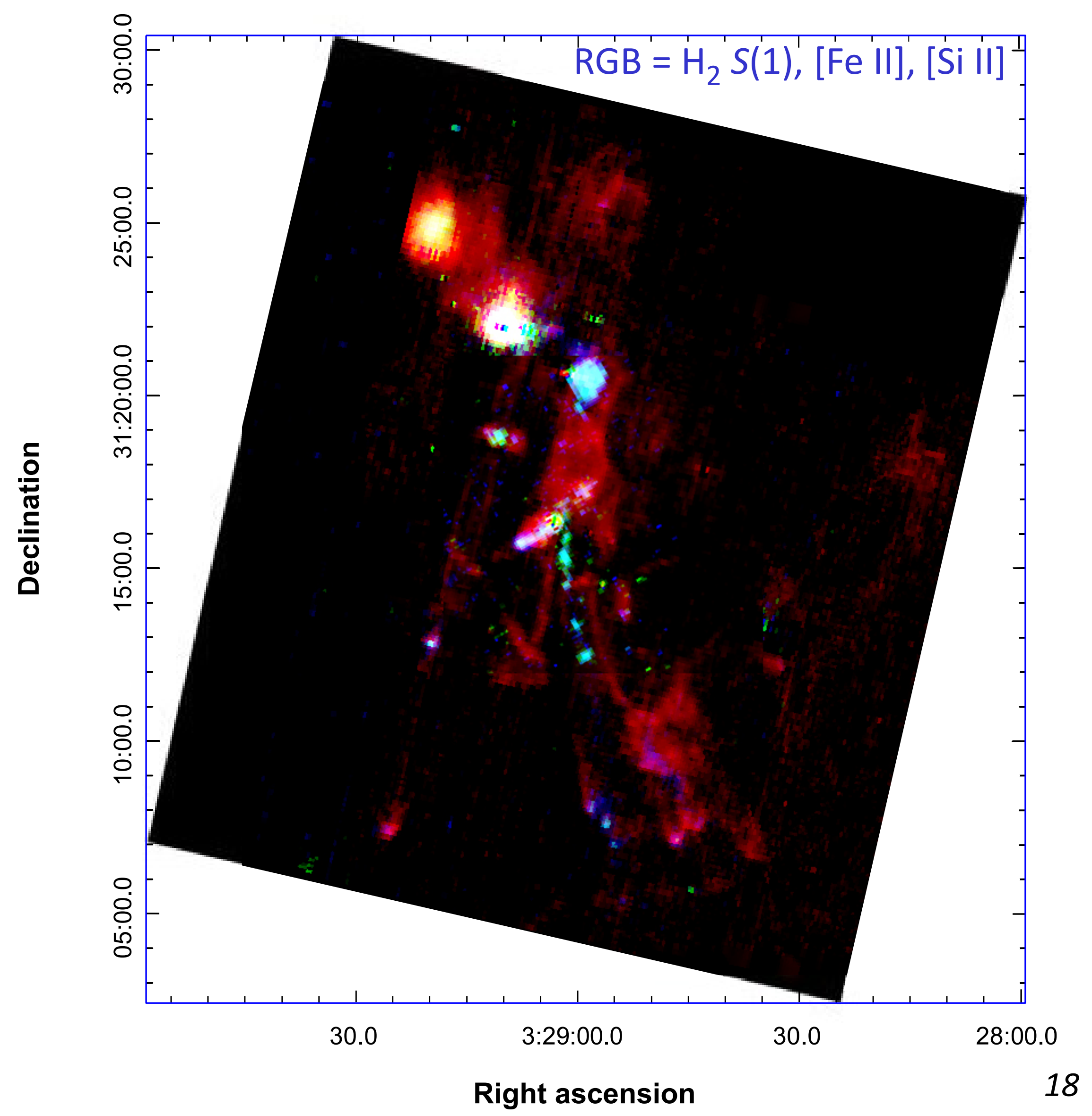
By age and luminosity, the outflow source for HH 7-11 (SVS 13A) will probably be an A star someday.

NGC 1333 (continued)

- ☐ From extinction map, get total binding energy: 10^{46} erg.
- ☐ From CO, get turbulent energy: ~2 $\times 10^{45}$ erg.
- ☐ From [Fe II], [Si II], and H2, get outflow momentum and energy injection rates: $1.4\times10^{-3}\ M_{\odot}$ km sec^{-1} year^{-1}, and $2L_{\odot} = 2\times10^{41}$ erg year^{-1}.
- ☐ From image, longest outflow dynamical time ~10^4 years.

⇒ **The outflows account for turbulence.**

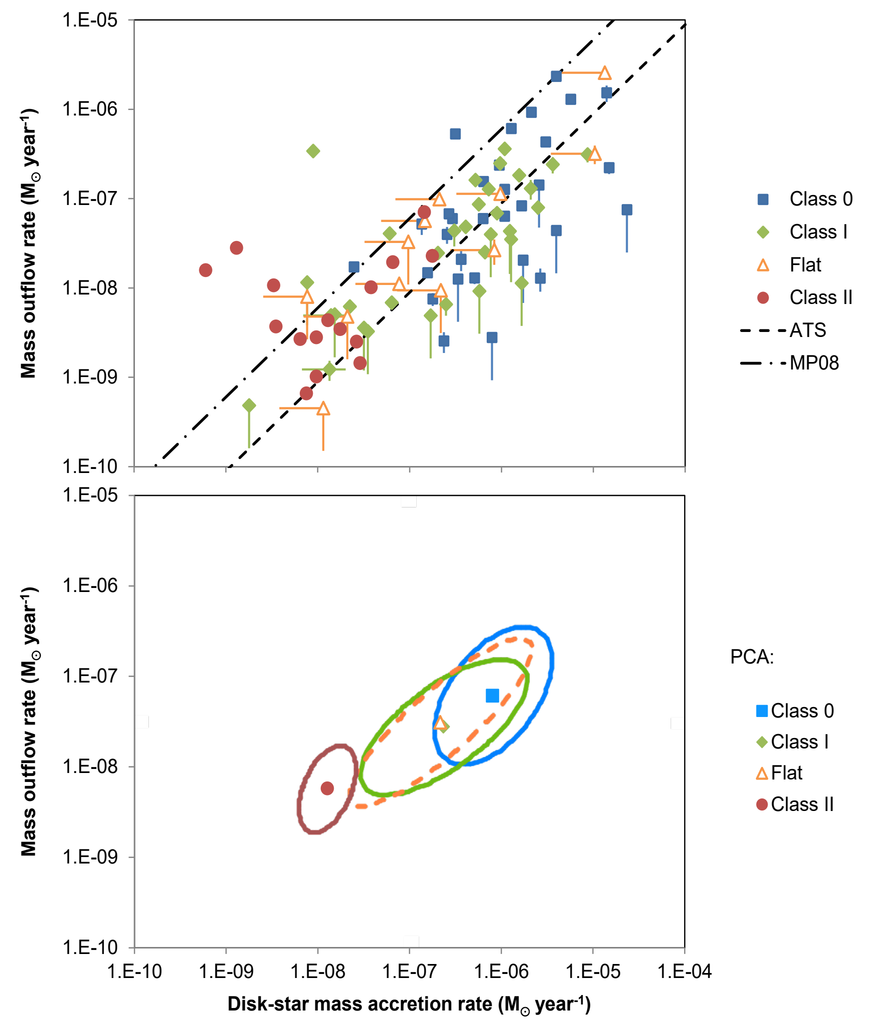
⇒ **They would have to stay numerous, to disrupt the cloud.**



Example: outflow evolution in the HIRMES Legacy Science Investigation

Using [O I], [Si II], and [Fe II] (Watson+ 2016):

- ☐ Protostellar mass ejection rates $\dot{M}_w$ track accretion rates $\dot{M}_a$ as they evolve through YSO classes 0, I and II.
- ☐ Typically the bipolar outflows seen in mm-wave CO are 90-99% entrained matter.
- ☐ Large range of branching ratio, $\dot{M}_w / \dot{M}_a$, may indicate that all three proposed magnetocentrifugal acceleration mechanisms are represented among protostars.
  - Accretion-powered stellar winds (e.g. Matt & Pudritz 2008)
  - X winds (e.g. Shu et al. 2000)
  - Disk winds (e.g. Königl et al. 2000)
- ☐ Need to add kinematic information from velocity profiles to extend to momentum ejection rate.

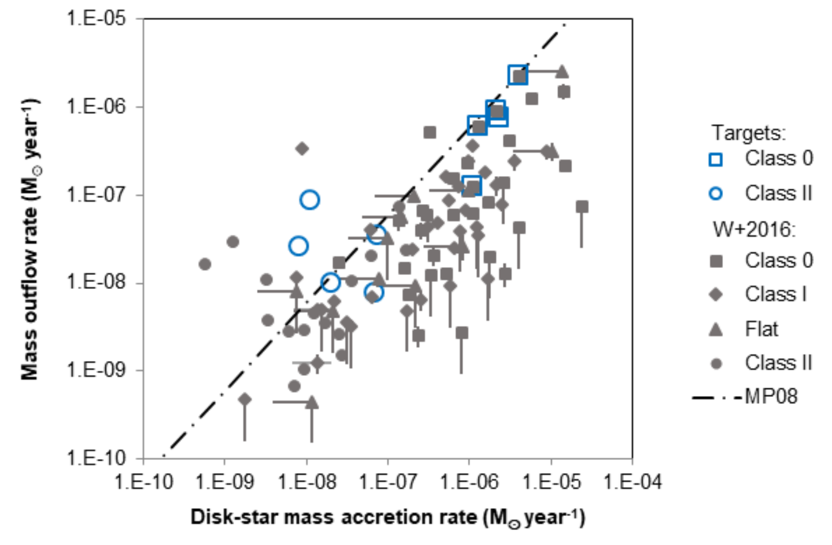


Watson+ 2016

Example: outflow evolution in the HIRMES Legacy Science Investigation (continued)

So we proposed to select a small sample biased toward the ends of the evolutionary sequence, and make spatially and spectrally resolved images, with goals of

- ☐ extracting rates of mass, momentum, and kinetic-energy outflow, using both “bolometric” and kinematic means;
- ☐ making precise and accurate $\dot{M}_w / \dot{M}_a$ measurements to constrain the (unresolvable) outflow footpoint locations;
- ☐ determine the angular momentum outflow rate and search for outflow rotation, already reported in one of our targets (DG Tau B; Zapata+ 2015).
- ☐ [O I]: high velocity resolution imaging; [O I] and [Si II]: deep medium-resolution imaging.



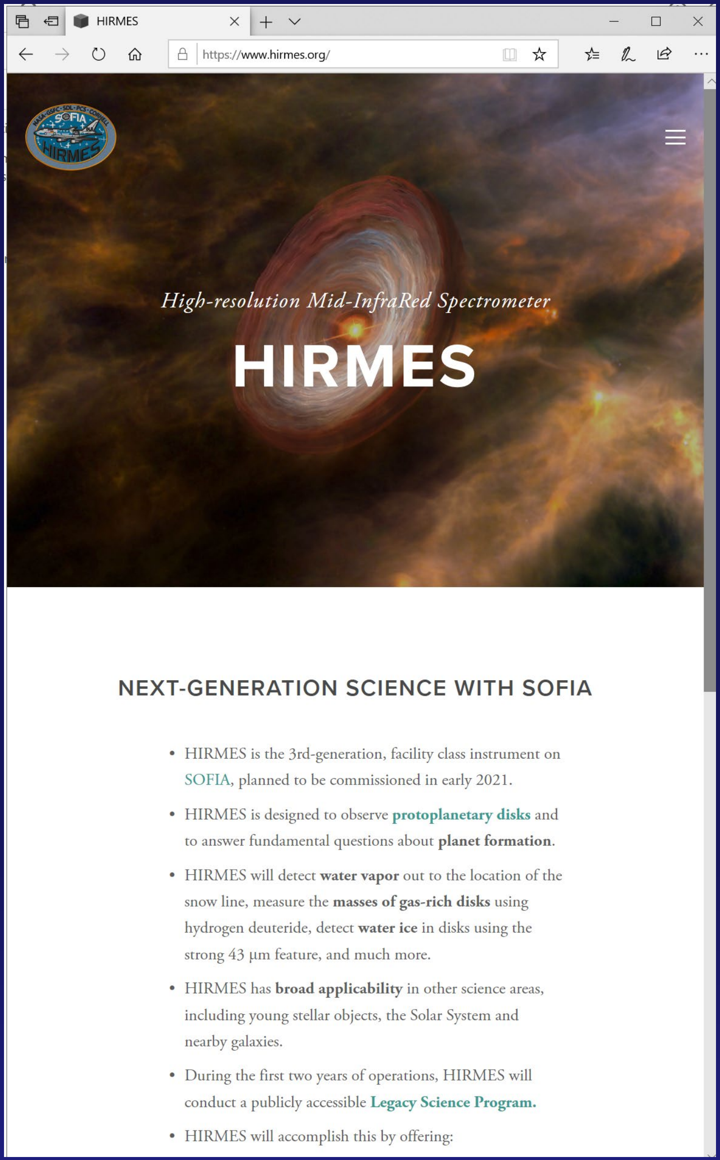
Target	Luminosity (solar)	Peak line flux (W m^{-2} per pixel) [Si II] 34.8 µm	Peak line flux (W m^{-2} per pixel) [O I] 63.2 µm	Wall-clock time (hours)
Class 0 objects (low-mass)				
HOPS 325	6.2	1.6E-17	1.6E-16	3.0
HH 211	3.6	1.0E-17	1.0E-16	11.7
HOPS 10	3.3	4.0E-17	4.0E-16	1.9
HOPS 32	2	4.5E-17	4.5E-16	1.9
SST J033327	1.7	5.8E-18	5.8E-17	6.4
Class II objects (low-mass) with outflows				
DG Tau	6.4	4.5E-17	4.5E-16	1.9
DG Tau B	1	1.8E-17	1.8E-16	3.1
FS Tau (A,B)	1.4	1.3E-17	1.3E-16	1.9
UY Aur	3.1	1.6E-17	1.6E-16	1.9
RW Aur (A,B)	3.2	5.0E-18	5.0E-17	6.4
Total				40.0

Summary

The grasp of SOFIA-HIRMES in star-formation feedback is unprecedented:

- ☐ More sensitive than GREAT at wavelengths at which both instruments work.
- ☐ GREAT has better spectral resolution, but HIRMES's resolution is more than sufficient for outflow work.
- ☐ At least as sensitive as Herschel-PACS at wavelengths at which both instruments work(ed).
- ☐ Not as sensitive as Spitzer-IRS, but the difference is not enormous, due to HIRMES's much greater spectral resolving power.
- ☐ High-impact observations of nearby YSO outflows can be made in a relatively small number of SOFIA flights.

Visit us at www.hirmes.org.



High-resolution Mid-InfraRed Spectrometer

HIRMES

NEXT-GENERATION SCIENCE WITH SOFIA

- HIRMES is the 3rd-generation, facility class instrument on SOFIA, planned to be commissioned in early 2021.
- HIRMES is designed to observe **protoplanetary disks** and to answer fundamental questions about **planet formation**.
- HIRMES will detect **water vapor** out to the location of the snow line, measure the **masses of gas-rich disks** using hydrogen deuteride, detect **water ice** in disks using the strong 43 μm feature, and much more.
- HIRMES has **broad applicability** in other science areas, including young stellar objects, the Solar System and nearby galaxies.
- During the first two years of operations, HIRMES will conduct a publicly accessible **Legacy Science Program.**
- HIRMES will accomplish this by offering:

Preparing for SOFIA-HIRMES Science

The missing link between JWST and Herschel

- Science talks illustrating the full range of HIRMES' potential
- The HIRMES Instrument, status, and capabilities
- The HIRMES Legacy Science Program
- HIRMES synergies with other missions

June 22-24, 2020
Johns Hopkins University
Space Telescope Science Institute

For more information, visit

https://www.hirmes.org/2020-workshop