The Hourglass as seen with HST/WFPC2

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Motivation

- Herschel 36 (O7: V + sec, Sota et al. 2014) is a unique object.
  - Main ionizing source of the Hourglass Nebula (for most of M8 it is 9 Sgr).
  - ZAMS SB3 system: O7.5 V + O9 V + B0.5 V (Arias et al. 2010).
  - Prototype of large-R_{5495} extinction laws (Cardelli et al. 1989).
  - Herschel 36 C ($0\farcs25$ away) is another B star companion, deeply embedded in dust (Goto et al 2006 and talk by J. Maíz Apellániz).
- The nebula and its environment.
  - The Hourglass has a very high surface brightness.
  - Complex gas and dust distributions (Arias et al. 2006).
  - Several other interesting objects (Goto et al. 2006, Arias et al. 2006).
- Supplemental HST Cycle 16: last chance for FUV observations with WFPC2.

The data

- Archival WFPC2 data (GO 6227, 1995, PI: Trauger).
  - Hourglass in PC, WF2 to the W.
  - V and I filters: F547M + F814W.
  - Nebular filters: F487N + F502N + F656N + F658N + F953N.
- New WFPC2 data (GO 11 981, 2009, PI: Maíz Apellániz).
  - Hourglass in PC, WF2 to the E.
  - FUV to B-band filters: F170W + F255W + F336W + F439W.
  - R-band filter: F675W.
  - Larger coverage and second epochs: F487N + F547M + F656N + F814W.
- Archival 2MASS JHK_s photometry and IUE spectroscopy for Herschel 36.

Processing

- See Arias et al. (2006) for initial processing of GO 6227 data.
- Aperture photometry for point-like or quasi-point-like sources.
  - Frame-by-frame photometry in original (geometrically-distorted) data.
  - Selection of best exposure time as a function of magnitude.
  - Saturated-star photometry using techniques similar to that of Gilliland (1994) for GAIN=15 and Maíz Apellániz (2003) for GAIN=7.
  - Realistic (spatially-varying) background subtraction.
  - CTI, contamination, and aperture corrections.
  - Aperture and zero-point uncertainties added to final result.
  - Herschel 36 ghost discarded in long exposures.
- Large-area photometry for nebulosity.

The overall structure of M8

- The Hourglass has a much higher surface brightness than the rest of M8 (Figure 1).
- The eastern pillars point towards 9 Sgr (O4 V((f))z, Sota et al. 2014), the main ionizing source of M8.
- The southern limit of the Hourglass is a pillar pointing towards Herschel 36.
- The region around Herschel 36 shows higher extinctions than the Hourglass (Figure 1 and Arias et al. 2006): reddened holes among (even more extinguished) dark regions.
- Some regions (tunnel towards the SW, part of the Hourglass pillar) are relatively brighter in F547M with respect to F656N or F487N: they are illuminated by mostly non-ionizing radiation.

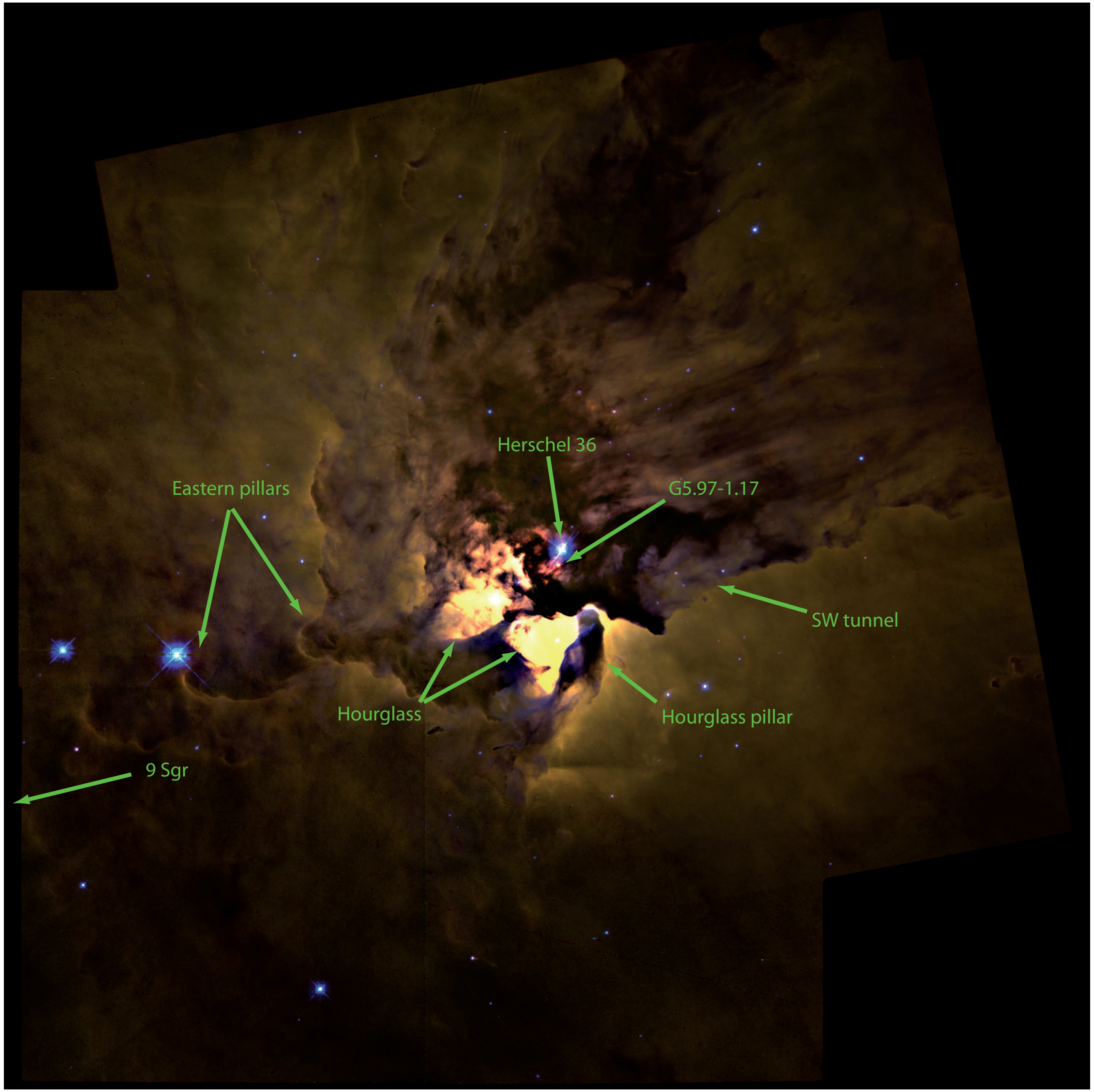

Figure 1. F656N (red) + F487N (green) + F547M (blue) WFPC2 mosaic of the extended region around the Hourglass. Redder regions indicate higher extinction in the nebular lines. In bluish regions scattered radiation is more significant. The field size is 205″ × 205″ (1.3 pc × 1.3 pc) and N is 45° CCW from top.

Herschel 36 and its reflection nebula

- Herschel 36 is the only bright point source in the FUV (Figure 2)...
- ...but it contains only 29±6% of the F170W flux in the PC.
- Only partial correlation between nebular emission and diffuse F170W (not red leak). The latter comes preferentially from the more extinguished regions: holes around Herschel 36 and NW part of the Hourglass.
- Explanation: FUV diffuse radiation is mostly (forward) scattered light.
- Proposed geometry (Figure 3):
  - Herschel 36 is creating a cavity inside the molecular cloud.
  - The direct light from the star arrives at us through a partially open hole.
  - The bright regions of the Hourglass are farther away than Herschel 36 and they are the visible surface of the molecular cloud directly illuminated by the star.
  - The cloud is porous e.g. SW tunnel.

Figure 2. F439W (red) + F336W (green) + F170W (blue) PC mosaic of the Hourglass. Herschel 36 is the bright point source in the upper right quadrant. The extended F439W and F336W is mostly of nebular origin while F170W is mostly reflected light. The field size is $34'' \times 34''$ (0.22 pc $\times$ 0.22 pc) and N is 45° CCW from top.

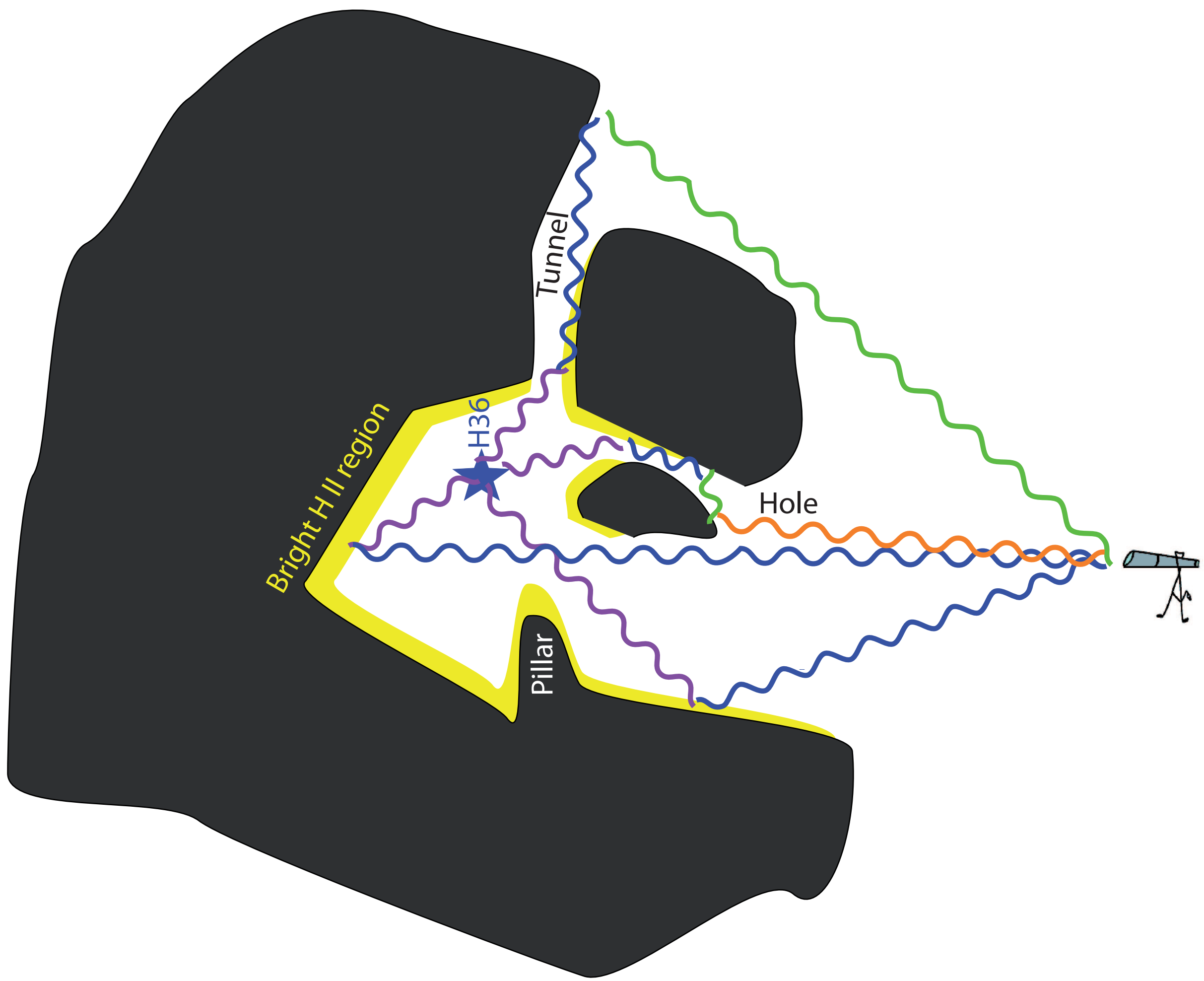

Figure 3. A toy model of the Hourglass region in M8 seen in cross section with respect to the plane of the sky. The path followed by radiation is represented by progressively redder lines as it is scattered in different parts of the nebula. The telescope position marks the direction of our point of view. The effect of external ionizing sources such as 9 Sgr is not included.

Herschel 36: optical+NIR analysis

- We use CHORIZOS (Maíz Apellániz 2004, 2013b) to measure the Herschel 36 extinction.
- Fixed luminosity class (5.0) and $T_{\rm eff}$ (38 400 K). Variable amount ($E(4405-5495)$) and type (R_{5495}) of extinction and logarithmic distance ($\log d$).
- Two alternative extinction law families: CCM (Cardelli et al. 1989) and new (Maíz Apellániz 2013a, Maíz Apellániz et al. 2014).
- Filters used: WFPC2 F336W + F439W + F487N + F502N + F547M + F656N + F673N + F675W + F814W, 2MASS J + H. K_s-band photometry excluded due to excess (see talk by J. Maíz Apellániz).
- Results (Table 1 and Figure 4): the new extinction laws provide a better fit to the optical+NIR data, especially for F336W.
- The original CCM paper used Herschel 36 as an anchor point for large-R_{5495} extinction laws but overestimated the amount of extinction ($E(B-V)$ = 0.89) and underestimated R_{5495} (5.30).

Quantity	CCM laws	New laws
$\chi^2_{\rm red}$	5.3	2.0
$E(4405-5495)$	0.883±0.008	0.784±0.008
R_{5495}	5.098±0.073	5.942±0.096
$\log d^*$	3.049±0.007	3.023±0.007
$E(\rm F439W - F547M)$	0.954±0.008	0.835±0.008
$A_{\rm F547M}$	4.512±0.037	4.670±0.038
$\rm F547M_0$	5.743±0.033	5.613±0.035

* Do not trust: it assumes a single, typical MS star.

Table 1. Results of the CHORIZOS fits for Herschel 36.

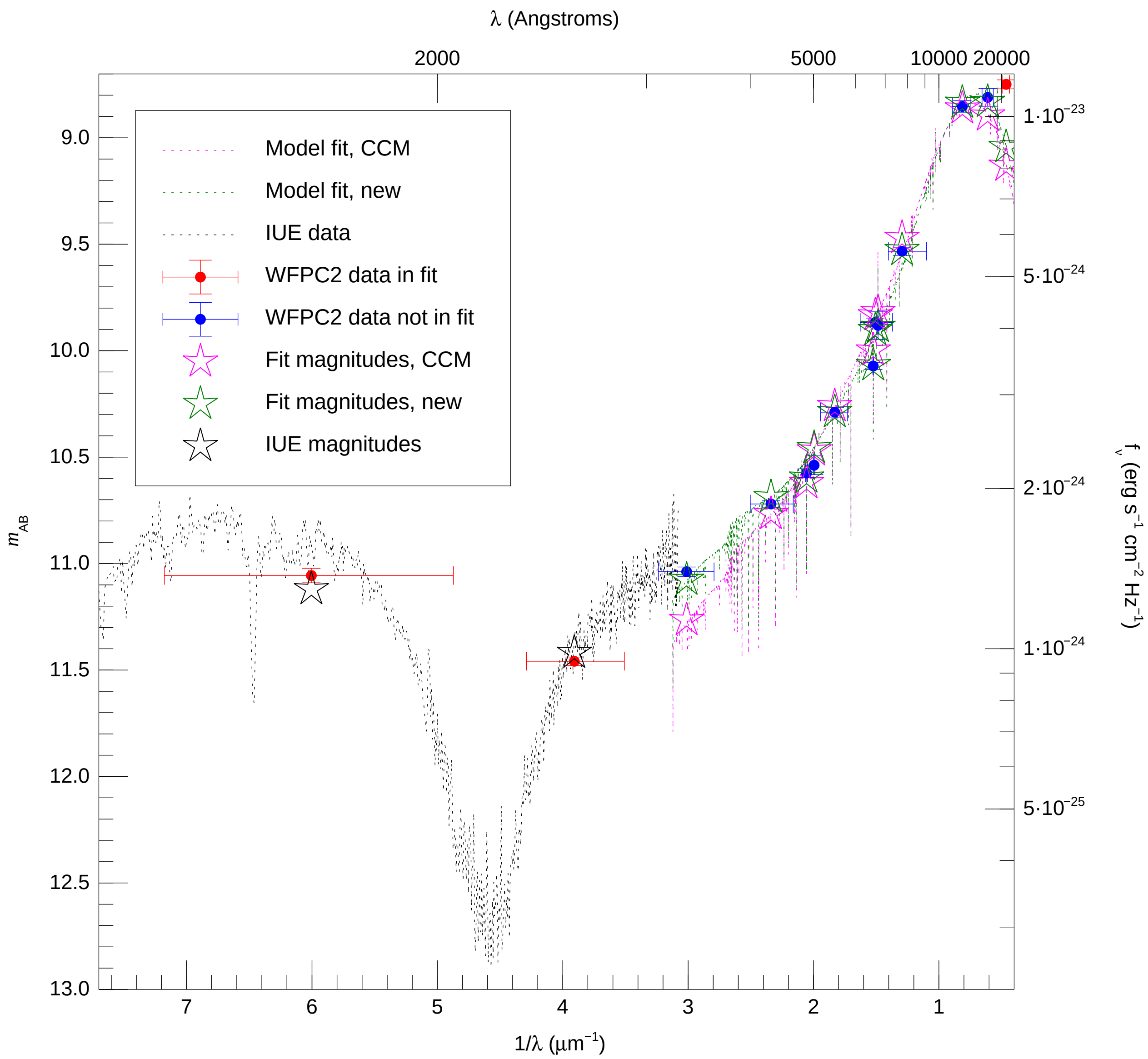

Figure 4. WFPC2+2MASS photometry, CHORIZOS fits to the optical+NIR photometry using the CCM and new families of extinction laws, and IUE spectroscopy of Herschel 36. The synthetic magnitudes are also shown for the two fits and the IUE spectroscopy. Note that the new extinction laws provide a better fit than the CCM ones.

Herschel 36: onto the UV

- We compare the IUE spectroscopy with the F170W + F255W magnitudes (Figure 4). There is agreement between the IUE and WFPC2 fluxes: The IUE extraction corresponds to the point source (it does not include the reflection nebula).
- Discontinuity between the CCM fit to the optical+NIR data and the IUE spectroscopy at the UV-optical boundary. Agreement with large-R_{5495} extinction laws measured in 30 Doradus (Maíz Apellániz et al. 2014).
- We calculate the UV extinction law A_λ/A_{5495} by dividing the measured IUE flux by the intrinsic TLUSTY SED derived from CHORIZOS and the new extinction laws (Figure 5):
  - The R_{5495} = 5.0 CCM law works better than the R_{5495} = 5.3 CCM law (the value used by CCM).
  - The 2175 Å bump is weaker than in the CCM laws.
  - Explanation: CCM used the wrong value of $E(4405 - 5495)$.

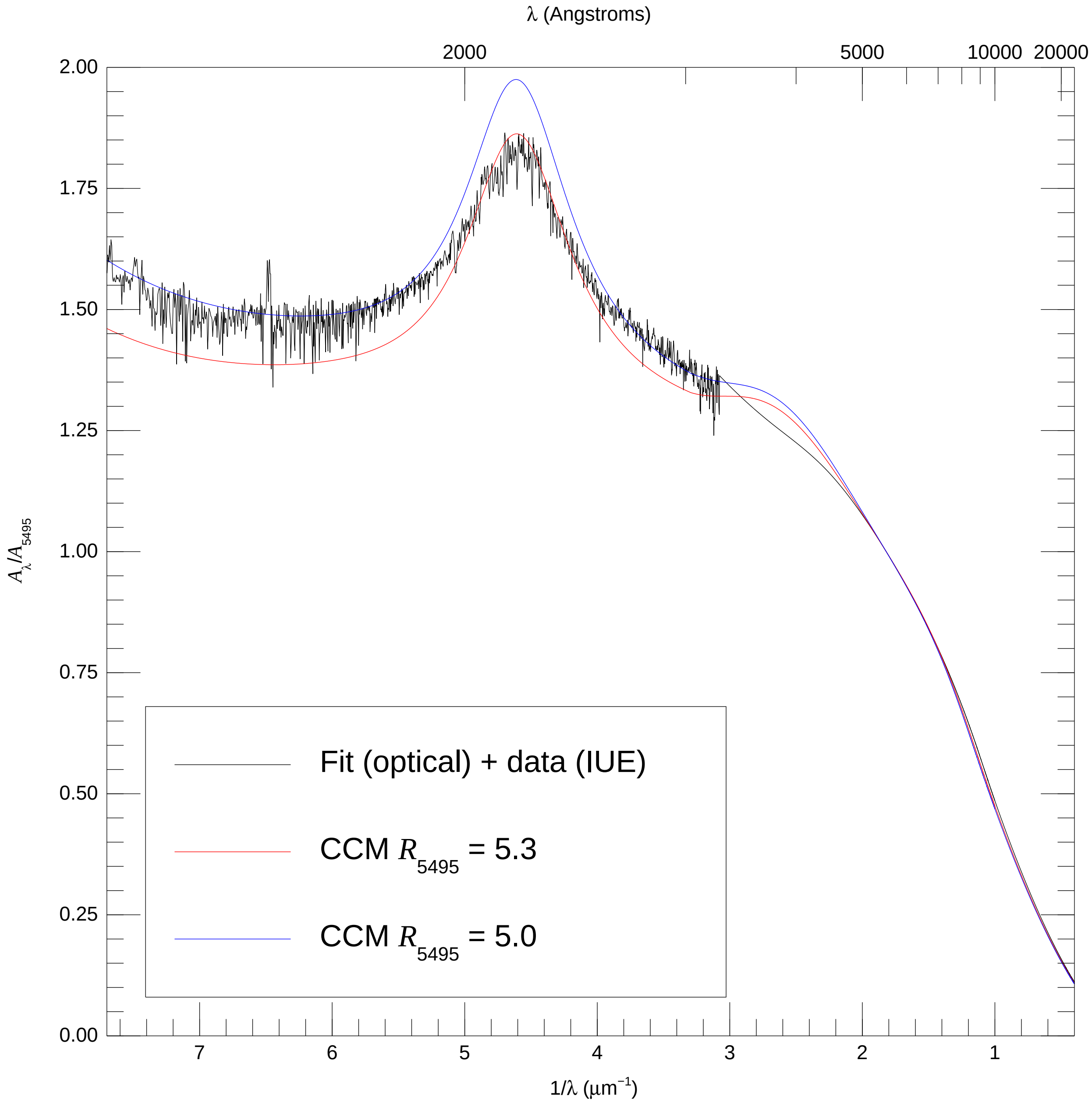

Figure 5. The Herschel 36 extinction law. The optical+NIR part is a CHORIZOS fit to the WFPC2 data using the new family of extinction laws. The UV part is derived from the IUE data and the TLUSTY intrinsic SED obtained with CHORIZOS. Two CCM extinction laws are shown for comparison.

Other sources in the Hourglass

- Only a handful seen in most optical filters.
- The Herschel 36 multiple system (Table 2, objects within $5''$ of A):
  - We have not attempted to resolve the embedded star Herschel 36 C (large contrast in the optical and we are using aperture photometry).
  - Herschel 36 Ba is much brighter than Bb in F814W (Arias et al. 2006).
- Herschel 36 D $\equiv$ G5.97-1.17:
  - Ultracompact H II region proposed as a proplyd by Stecklum et al. (1998).
  - We measure a shift of $\sim$0.3 PC px ($0\farcs015$ or 19 AU) between 1995 and 2009 (Figure 6): this might correspond to the orbital motion around Herschel 36 with a minimum period of 17 000 a.
  - We determine the extinction from the Hα/Hβ ratio (F487N and F656N have low continuum contamination) assuming the same R_{5495} as for Herschel 36 A and obtain A_{5495} = 9.9±0.3 mag.

Component	Other name	Separation (″)	PA (°)	ΔF814W (mag)
Ba	KS 1-S	2.913	8.7	6.98
Bb	KS 1-N	3.484	4.3	∼14
C*	Herschel 36 SE	0.250	110.0	—
D	G5.97-1.17	2.903	123.3	6.40
E		0.740	201.7	4.82
F		4.196	125.8	10.0
G		2.774	272.6	10.3
H		2.415	112.0	10.4
I		3.456	168.2	12.3
J		1.660	313.0	∼13

* Data from Goto et al. (2006).

Table 2. The multiple system Herschel 36. The separations, positions angles, and magnitude differences are all with respect to A.

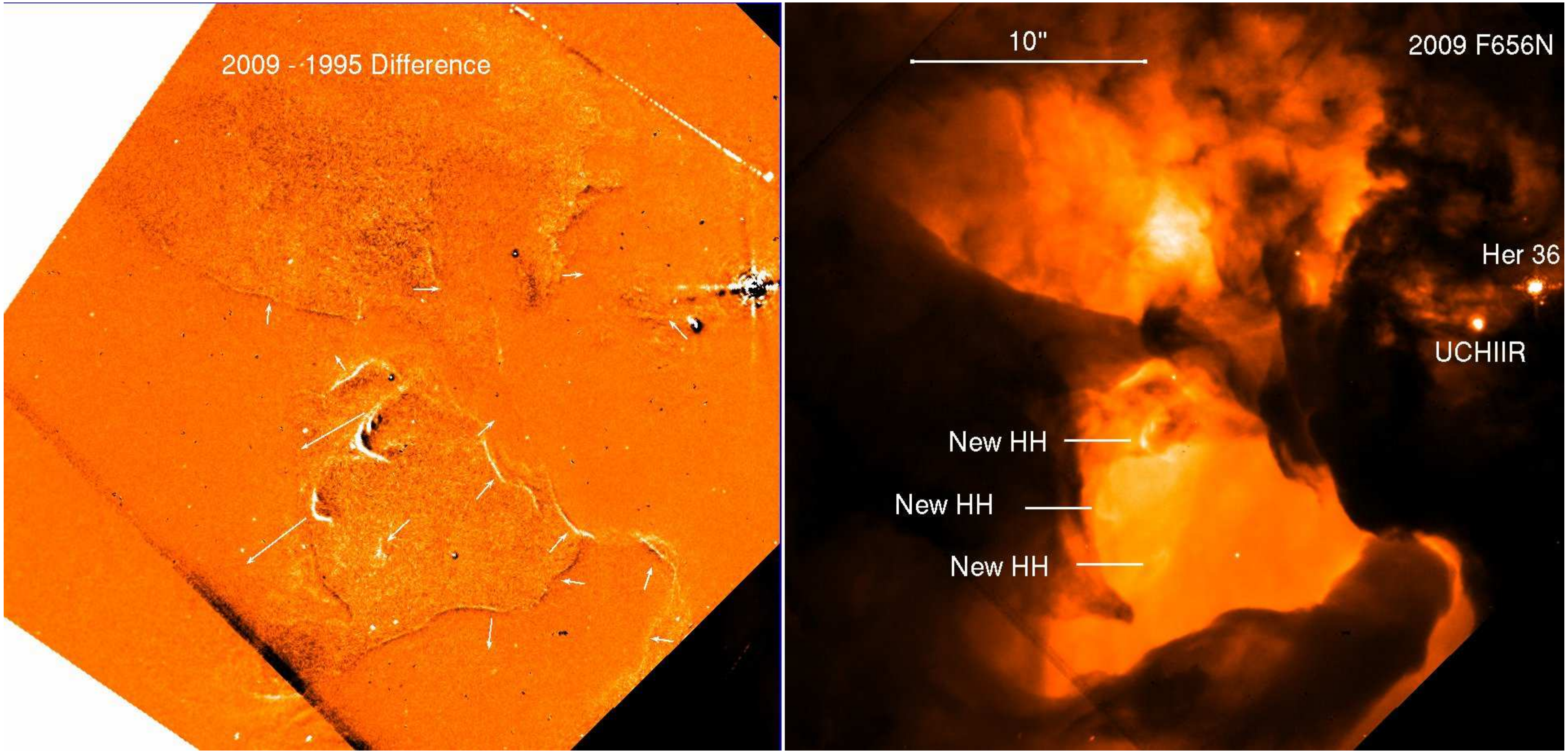

Figure 6. (left) Differential F656N image between 2009 and 1995. Whiter colours indicate stronger emission in 2009. The white arrows mark the direction of the detected movement. Their lengths are proportional to the modulus of the motion vectors. North is up and east is left. (right) F656N image of the same region. Herschel 36, the ultracompact H II region G5.97-1.17, and the newly discovered Herbig-Haro objects are labelled.

Herbig-Haro objects and nebular expansion

- The comparison between new and archival WFPC2 images also reveals internal movements in the Hourglass Nebula.
- Three new Herbig-Haro objects identified (Figure 6).
- The HH nebular structures are displaced $0\farcs2$-$0\farcs3$ during the interval between observations, indicating tangential velocities of 85-130 km/s.
- A variety of nebular structures also show displacements of up to 1 px ($0\farcs045$), suggesting an anisotropic expansion of the whole Hourglass Nebula (Figure 6).

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