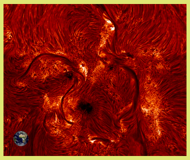
THE SUN WITH ALMA: JETS & CONTRAILS!



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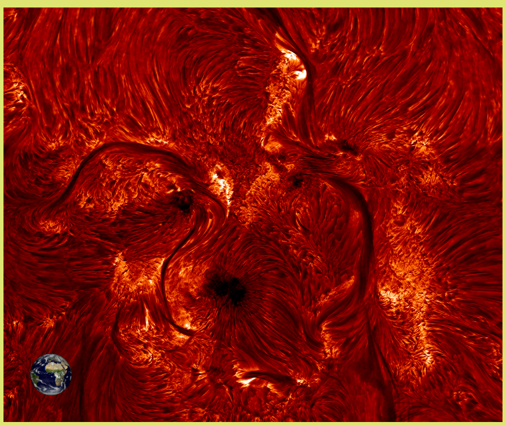
ALMA has started observing the Sun. ALMA will "game-change" solar physics thanks to:

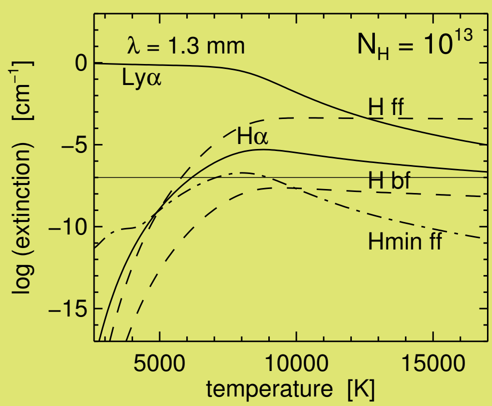
- **sharpness**. Obvious from the $\sim D/\lambda$ diffraction limit. The sharpest solar imager so far is the Swedish 1-m telescope on La Palma, observing wavelengths close to 1 μm. At 1 mm wavelength and 10 km baseline ALMA gains an order of magnitude.
- **ease of interpretation**. ALMA is a linear thermometer of optically thick structures in the solar chromosphere, whereas all other chromospheric diagnostics (strongest optical lines, ultraviolet lines and continua) suffer severely from non-LTE scattering. Reason: at mm wavelengths the main extinction processes are H I free-free transitions in hot gas and H-minus free-free transitions in cool gas. These are thermal with the Planck function as source function for which the Rayleigh-Jeans limit holds. Thus, for optically thick features the measured intensity equals the feature temperature.
- **enormous chromospheric opacities**. Less easy to grasp, and in fact severely underestimated in all solar ALMA prediction studies so far, including all numerical simulations. Explanation below. Summary: they are far out of statistical equilibrium after hot events in subsequent cooling gas in which they maintain the high values reached in the hot phase for minutes thereafter. The solar chromosphere is pervaded by fast small heating agents ("jets" producing the hot corona) that leave long slender cooling trails observed as opaque "fibrils" in Hα. Much like aircraft jet engines drawing long cooling contrails in our own atmosphere. These ubiquitous heating events and contrails will be much better visible at the ALMA wavelengths.



Hα image mosaic from the Dutch Open Telescope. The Hα chromosphere consists of a dense mass of long fibrils wherever there is magnetic activity on the solar surface. No other spectral line shows these fibrils at such length. The reason for this extraordinary display is slow non-equilibrium balancing in Lyα in cooling gas. The large 10 eV Lyα jump has very few collisional lower-to-upper excitations at low temperature because the Einstein relation for collisional balancing imparts Boltzmann temperature sensitivity $\sim \exp(-h\nu/kT)$. In a hot event this balancing is fast (seconds), which together with the enormous Lyα opacity (giving small thermalization length even at tremendous resonance scattering) produces large populations, close to the instantaneous Saha-Boltzmann value, to the top of the hydrogen atom controlling Hα, H ionization, and the ALMA H I free-free continuum. During subsequent cooling these hydrogen-top populations stay for minutes at these high values, so reaching non-equilibrium overpopulations that typically reach 10 orders of magnitude! For a tutorial on such "post-Saha-Boltzmann extinction" (PSBE) see Rutten (2017b).

Rutten & Rouppe van der Voort (2017) identified an exemplary Hα fibril as a cooling-gas contrail occurring 3-5 min after a jet-like heating event passed that reached 1.5 MK. In the meantime I found many more such PSBE contrails; I suspect that all fibrils are post-jet contrails but that most heating events are too small for current telescopes. Stuff for ALMA! The quest is to identify the heating mechanims ("coronal heating problem"): magnetic reconnection and/or Alfvénic torsion waves?

[1] *Least known astrophysics institute in The Netherlands, but the most centrally located and with by far the highest publications/FTE effectivity ratio.*



Saha-Boltzmann hydrogen extinction coefficients for solar gas with hydrogen density characteristic of the chromosphere. These curves are good approximations in hot instances. Values above the horizontal line at $y = -7$ imply optical thickness for a feature 100 km thick. Above 6000 K H I free-free already wins from Hα; yet more at longer wavelengths since $\alpha_\nu^{\rm ff} \sim \lambda^2 N_{\rm e} N_{\rm ion}\, T^{-3/2}$. Above 13000 K H I free-free even exceeds Lyα, making ALMA the best diagnostic spectrum-wide to detect (and measure!) small hot events.

In subsequent cooling (drastic because hydrogen recombination eats much energy) the extinction values stay at the previous high-temperature peak values while the temperature drops. Hα fibrils have $T \approx 5000$ K but their PSBE Hα extinction remains 10^3 too large, their PSBE H I free-free extinction 10^5 too large. Such PSBE features in Hα will be much more opaque in ALMA images. ALMA will show the fibrilar Hα chromosphere with enormous opacity boost – and to boot measure hot-jet and PSBE-contrail temperatures on very fine scales.

More detail in Rutten (2017a). It ends with a dozen specific predictions for what ALMA will observe and not observe on the Sun, concluding: *"Hopefully these predictions will soon be verified with actual ALMA observations. I look forward to be proven right or wrong."*

My expectation: lovely ALMA will settle the coronal heating problem!

References

Rutten, R. J. and Rouppe van der Voort, L. H. M.: 2017, *A&A* **597**, A138

Rutten, R. J.: 2017a, *A&A* **598**, A89 (*complimentary to M.W.M. de Graauw*)

Rutten, R. J.: 2017b, IAU Symp. 327, in press, ArXiv 1611.05308