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SFB 956 - Conditions and Impact of Star Formation

Surprisingly weak fine-structure line emission from S140

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S140

- S140 is a well studied molecular cloud/photon-dominated region (PDR)/HII region at a distance of 764pc
- Outer interface PDR is illuminated by HD211880 providing a UV field of $G_0 \approx 300$.
- Deeply embedded star formation visible through infrared sources IRS1-3 with luminosities of 10000L⊙ (IRS1), 2000L⊙ (IRS2), 1300L⊙ (IRS3).
- Interface and central cluster prominent in molecular lines (low-*J* CO isotopes).
- IRS1 dominates energy input, clear peak in IR continuum and CO maps.

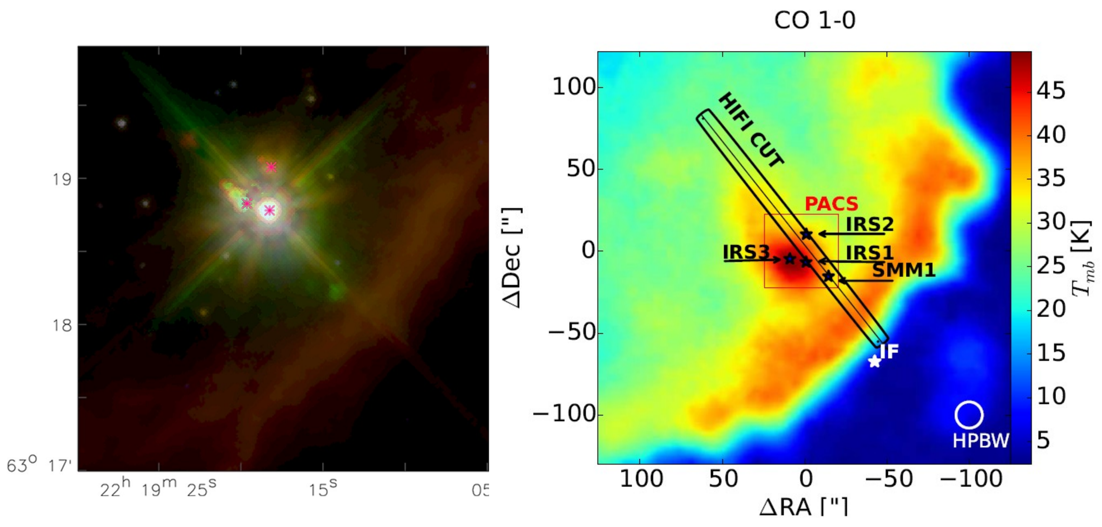

Figure 1: Existing S140 maps. Left: IRAC (3.6, 5.6, 8μm). Positions of the three IR sources are marked. Right: CO 1-0 peak intensity map (IRAM 30m) with an sketch of previous Herschel observations of the source. Koumpia et al. (2015)

SOFIA/GREAT observations

The fine structure lines [OI] (63μm) and [CII] show a prominent peak, but offset from IRS1 by 20" to the north (probably associated with IRS2).

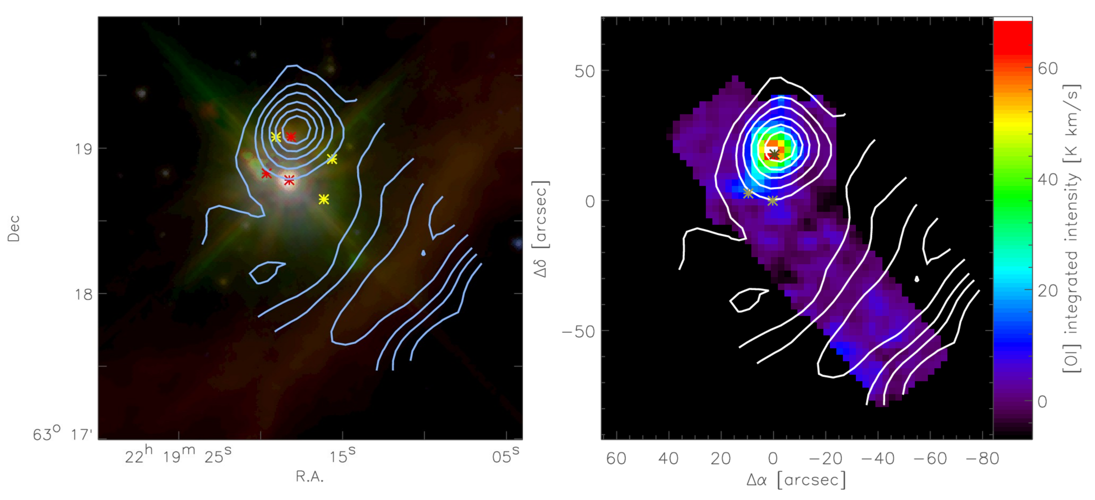

Figure 2: Integrated line intensities of [CII] and [OI]. Left: IRAC three-color image (3.6,5.6,8.0μm) superimposed by contours of [CII] intensity at 50,70,90,120,150,180 K km/s. Right: Same [CII] contours over [OI] intensities. The asterisks mark IRS1-3. Ossenkopf et al. (2015)

CO lines tracing the molecular gas are more extended. High-*J* CO peaks between the infrared sources.

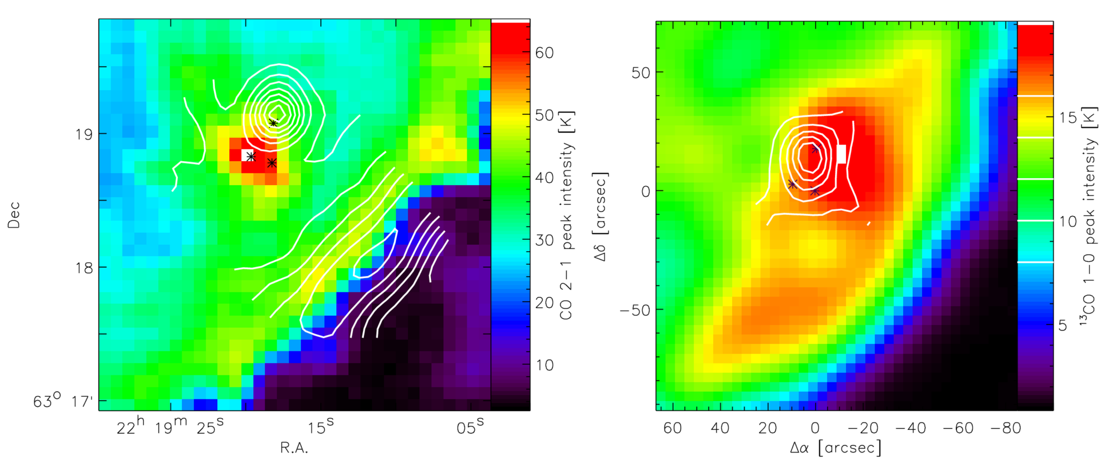

Figure 3: Peak intensities. Left: ^{12}CO 1-0 with contours of [CII] (15-45K), Right: ^{13}CO 1-0 with contours of CO 16-15 (8-16K).

Line profiles show self-absorption in [OI] and a 1km/s velocity offset for the emission from the fine-structure line emission peak.

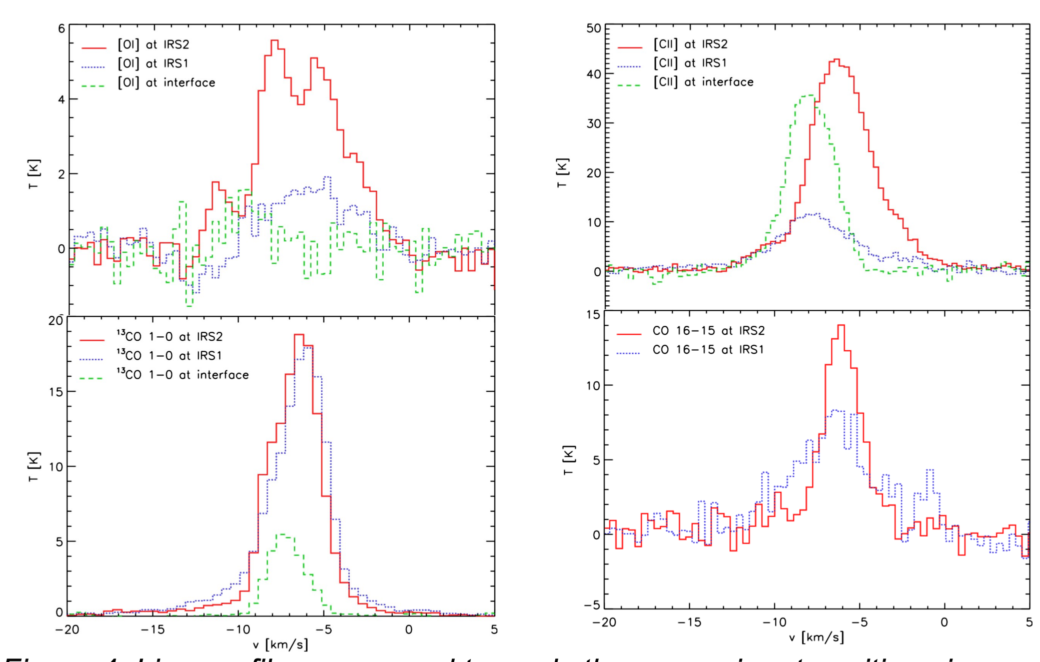

Figure 4: Line profiles measured towards three prominent positions in a synthetic 17.3" beam. The emission from the external interface is only strong in [CII].

Properties of the peak

The emission peak is resolved in the 6.6″ SOFIA beam at 63μm. The emission of [OI] and [CII] from IRS2 can be described by a Gaussian intensity distribution with FWHM = 8.3″ = 0.03pc. From the fitted peak intensity we can compute the total luminosity in all lines:

- [OI]: 76 K km/s → 0.28 L⊙
- [CII]: 212 K km/s → 0.05 L⊙
- CO 16-15: 46 K km/s → 0.01 L⊙

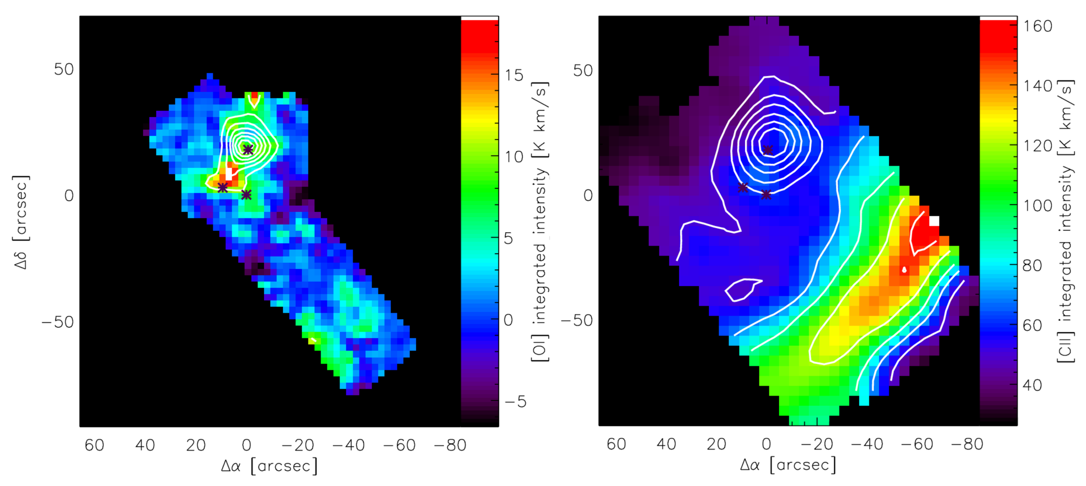

Figure 5: Integrated intensity maps before (contours) and after subtracting the Gaussian intensity peak (colors). Left: [OI] 63μm, Right: [CII].

The common fit suggests that the same gas is responsible for [OI] and [CII]. Total mass: ≈ 40 M⊙. However, only in 7% of that mass carbon is ionized providing the observed fine-structure line emission.

Fine-structure line deficit

Models of photon-dominated regions (PDRs) link the fundamental physics of the photoelectric heating efficiency to the ratio between the observable flux in far infrared lines and continuum. Typical Galactic values fall between 10^{-3} and 0.01. They have been observed in many PDRs.

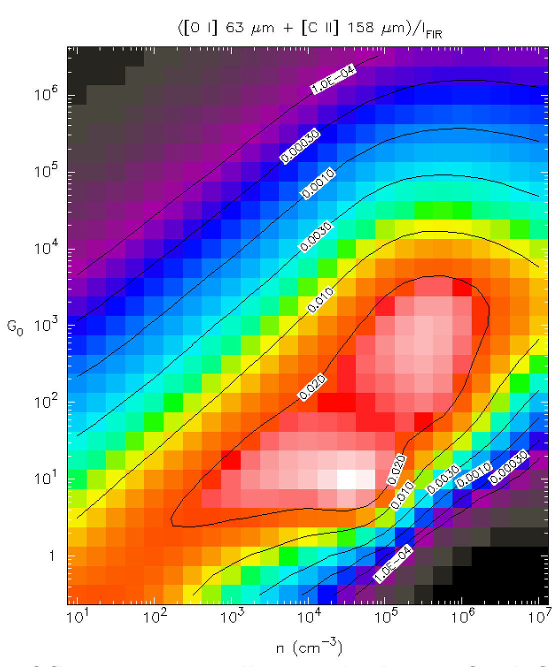

Figure 6: Ratio of fine-structure line emission to far infrared continuum predicted from a standard face-on PDR model (Kaufman et al. 1999). For the UV field of $G_0 \approx 10^5$ and densities above 10^5 cm^{-3} expected at the infrared sources, the model predicts line intensities of 1-3 × 10^{-3} of the continuum flux.

We can measure the complete sum of the gas line cooling by adding the cooling power of the full CO ladder obtained from IRAM and SOFIA observations. The total infrared continuum (TIR) is obtained by combining FORECAST, SPIRE and SCUBA data.

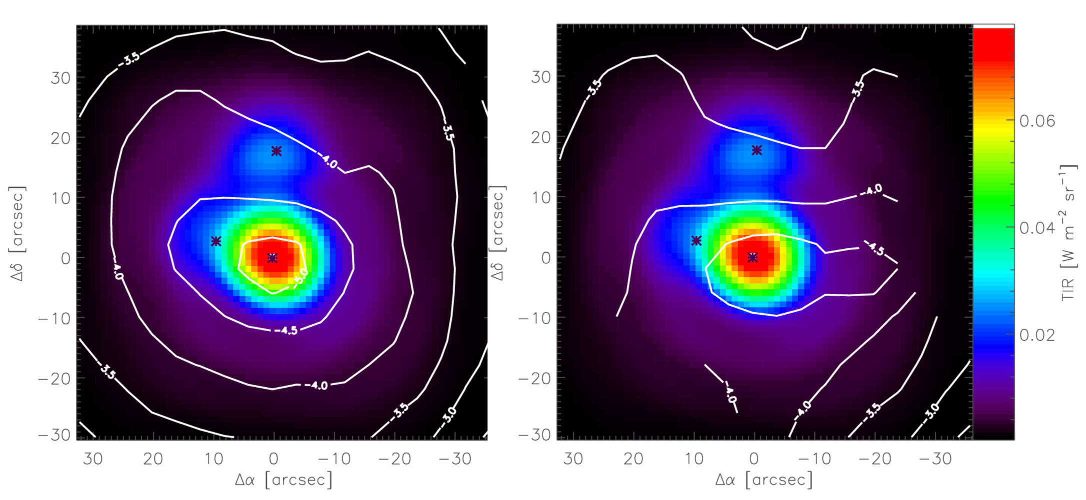

Figure 7: Comparison of the line cooling with the total infrared continuum. Colors show the continuum flux. Contours show the decadic logartithm of line to continuum ratio. Left: [CII]/TIR. Right: ([CII]+[OI])/TIR

The **observed [CII]/TIR ratio is 10^{-5} – 10^{-4}** towards the infrared sources, the ([CII]+[OI])/TIR ratio is only higher by a factor 3. These numbers are lower than typical Galactic values by a factor 10-100! They match the criterion for a **far-infrared line deficit as observed in many ULIRGS**. Standard PDR models cannot reproduce the line deficit.

New PDR model

Instead of using plane-parallel PDR models the geometry of the source has to be taken into account. We find an inside-out PDR with the hot gas, bright in [CII] and [OI], concentrated in a small volume around the protostellar sources and cooler material, providing most of the continuum flux, in a more extended envelope.

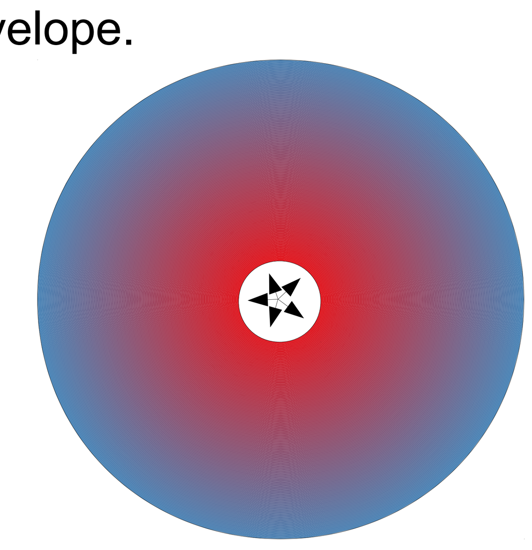

Figure 8: Sketch of the toy PDR model used to simulate the chemical and temperature structure of the gas around the embedded sources.

Already without a dedicated fit to the line profiles a first run for some limiting densities shows a reasonable resemblance of the observed lines. The toy model can easily reproduce the observed line deficit.

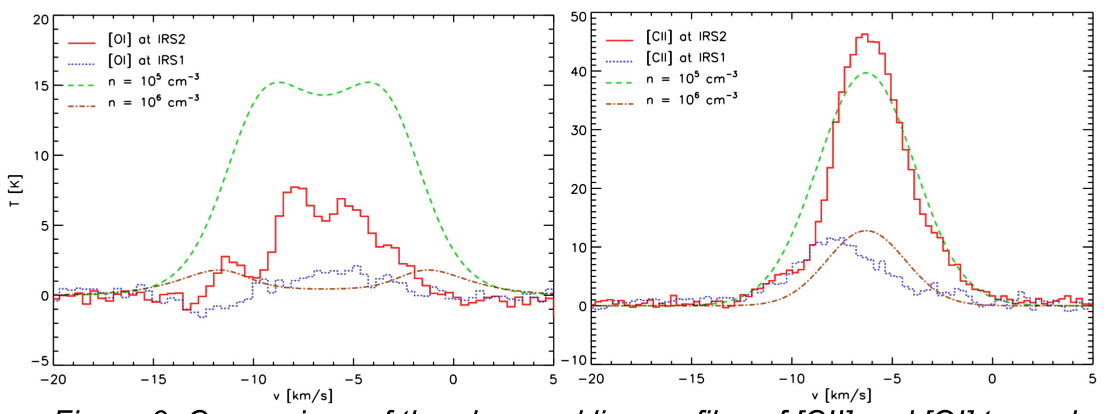

Figure 9: Comparison of the observed line profiles of [CII] and [OI] towards IRS1 and 2 with model predictions of an inside-out PDR model for assumed gas densities of 10^5 cm^{-3} and 10^6 cm^{-3}.

The main explanation for the line deficit is the small size of the emitting PDRs at high densities compared to the extended gas contributing to the far infrared continuum. For external galaxies this leads to a small beam-filling factor for the fine structure lines compared to the continuum.

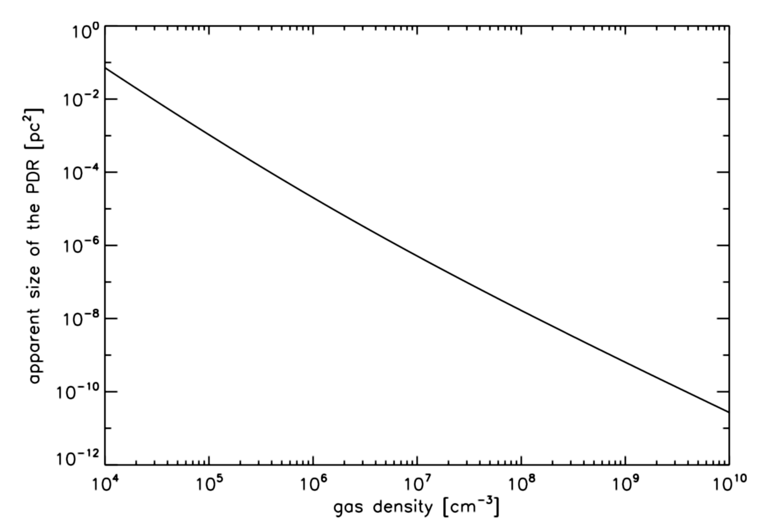

Figure 10: Size of a PDR around an HII region fed by a star emitting $10^{46.5}$ UV photons per second, representative for IRS1, as a function of the assumed gas density.

Conclusions

- Only the external interface of S140 behaves like a “normal PDR” at a moderate density of 2×10^4 cm^{-3}.
- IRS2 has an internal PDR dominating the fine-structure line emission from the whole region. That emission is still weak compared to the bright continuum flux. We find a clear line deficit.
- IRS1 is even more extreme. It dominates the infrared continuum from the whole region, but shows very little [CII] and [OI]. We measure an extreme line deficit.

We can explain the line deficit as a pure density effect in a homogeneous medium. High densities limit the physical size of the HII regions and PDRs leading to a small total line luminosity.
In such regions the main gas cooling occurs through

- Direct recombination cooling
- Gas-dust collisions with dust FIR cooling

In Galactic context S140 is an “ultraluminous infrared source”, i.e. it may provide a **template for a general explanation of the line deficit in ULIRGs**.