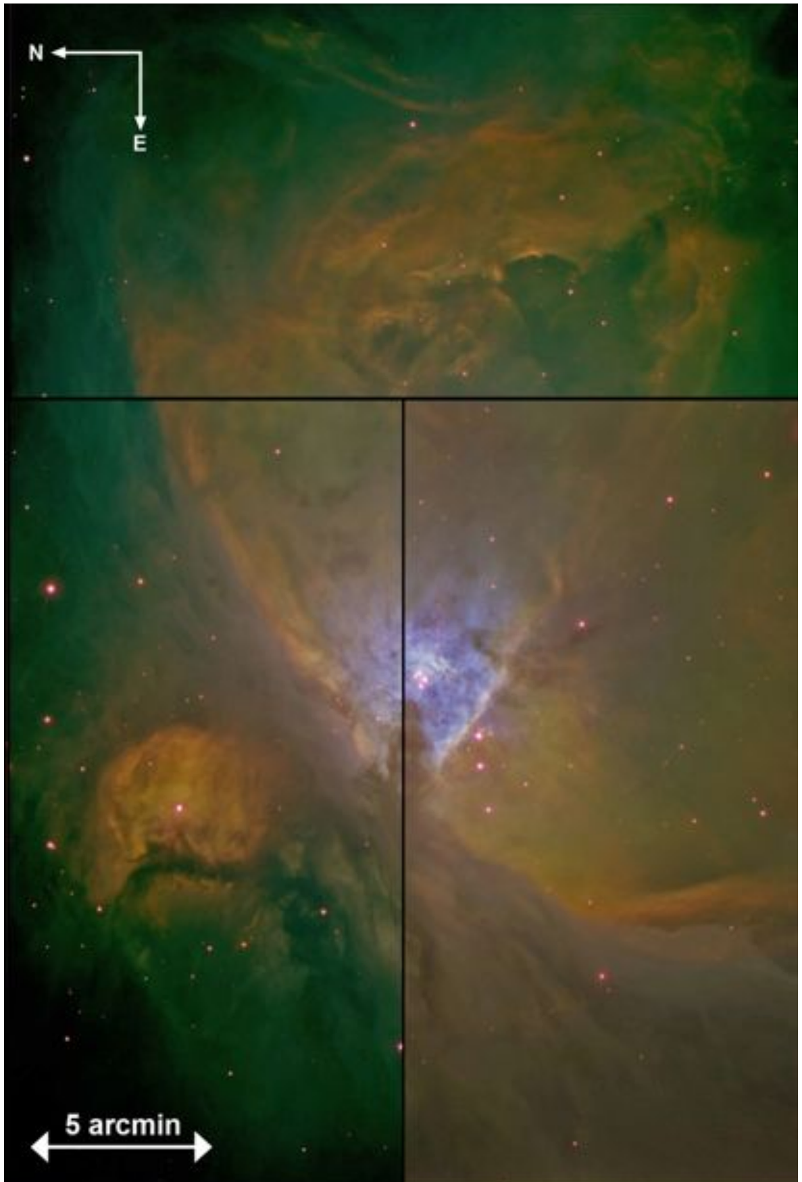


# M43, the little sister of the Orion nebula.

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Ángel R. López-Sánchez (AAO, Australia)

NCAC. July 17th 2012

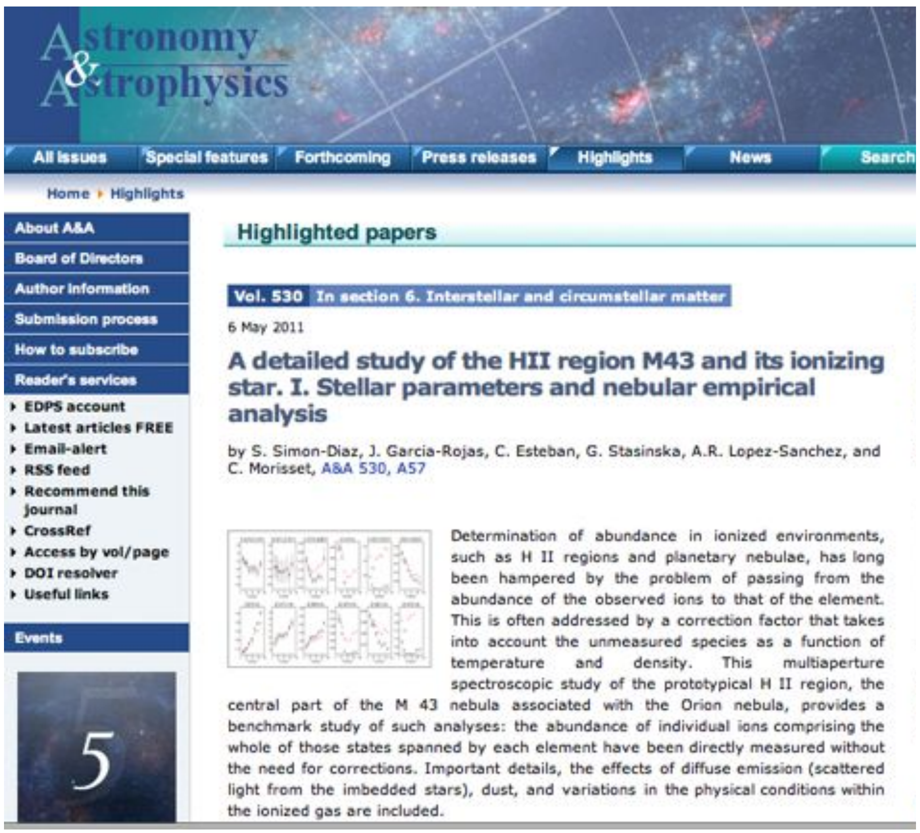
*A detailed study of the HII region M43 and its ionizing star.*

*I. Stellar parameters and nebular empirical analysis.*

Simón-Díaz, García-Rojas, Esteban, Stasinska, López-Sánchez & Morisset, 2011, A&A, 530, A57

*II. Stellar spectral energy distribution and nebular photoionization models.*

Simón-Díaz, Morisset, García-Rojas et al. (in preparation)



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Highlighted papers

Vol. 530 In section 6. Interstellar and circumstellar matter

6 May 2011

**A detailed study of the HII region M43 and its ionizing star. I. Stellar parameters and nebular empirical analysis**

by S. Simon-Diaz, J. Garcia-Rojas, C. Esteban, G. Stasinska, A.R. Lopez-Sanchez, and C. Morisset, A&A 530, A57

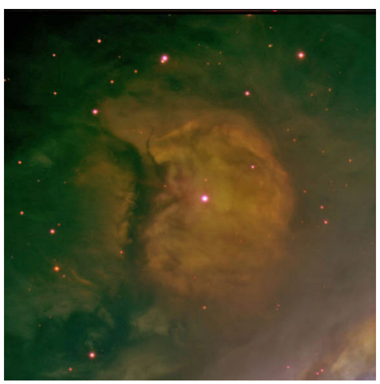
Determination of abundance in ionized environments, such as H II regions and planetary nebulae, has long been hampered by the problem of passing from the abundance of the observed ions to that of the element. This is often addressed by a correction factor that takes into account the unmeasured species as a function of temperature and density. This multiaperture spectroscopic study of the prototypical H II region, the central part of the M 43 nebula associated with the Orion nebula, provides a benchmark study of such analyses: the abundance of individual ions comprising the whole of those states spanned by each element have been directly measured without the need for corrections. Important details, the effects of diffuse emission (scattered light from the imbedded stars), dust, and variations in the physical conditions within the ionized gas are included.


Color composite image of the M 42+M 43 region (Simon-Diaz, S., et al., 530, A57)

# Motivations of the study

Combined study of Galactic HII regions and the associated massive OB-type stars to:

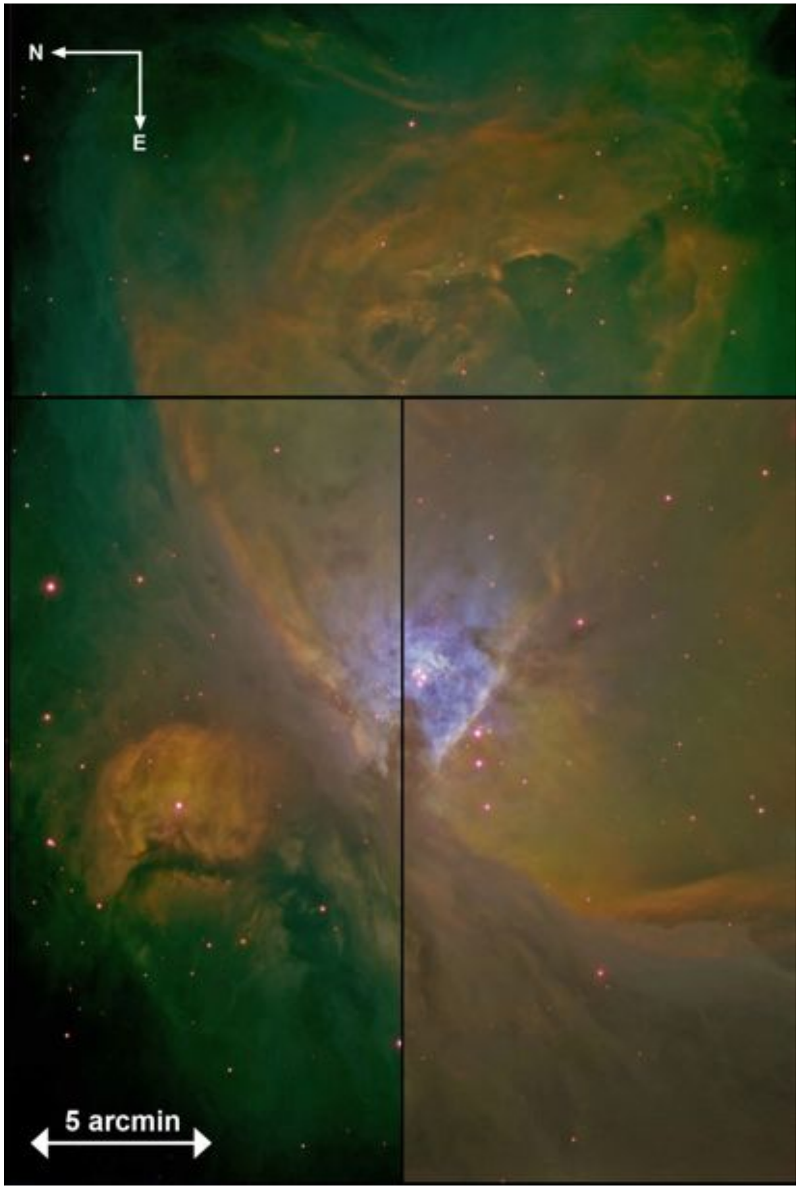
- Check the reliability of the ionizing spectral energy distributions predicted by the modern stellar atmosphere codes
- Step forward in the investigation of the cause of the nebular abundance discrepancy problem
- Investigate if present-day abundances derived from HII regions and B-type stars in agreement?






M43 is the first one but there are others…

# M43: the little sister of M42




• Bright nebula

• Apparently simple geometry

• Single ionizing source: HD37061, B0.5V-B1V star. Multiple system, but only one of the stars produce ionizing photons.

• Forms part of the very well studied Extended Orion Nebula (EON)

• Stellar abundances well known (see next talk by S. Simón-Díaz)

A simple case?

# Observations, strategy and tools (in a nutshell)

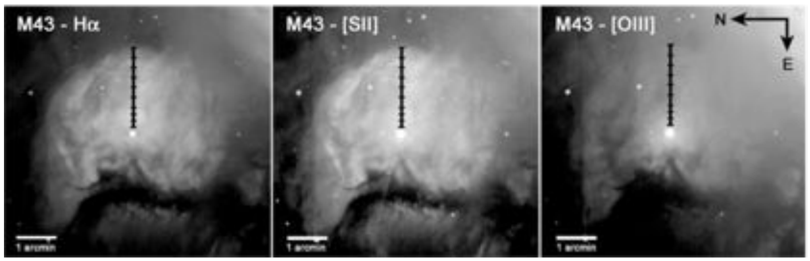
| | OBSERVATIONS AND INSTRUMENTS | | STRATEGY |
|---|---|---|---|
| HII regions | Narrow band images<br>Hα, Hαc, Hβc, Hβ<br>(+[OIII], [SII]) | WFC@INT | Nebular geometry<br>L(Hα), S(Hα)<br>Extinction maps |
| | Long-slit optical spectroscopy | ISIS@WHT<br>IDS@INT | Nebular physical properties<br>Nebular abundances<br>Ionization structure |
| OB stars | Optical spectroscopy | ISIS@WHT<br>IDS@INT<br>FIES@NOT | Stellar and wind parameters<br>Ionizing SEDs, $Q(H^0)$<br>Stellar abundances |

**TOOLS**

IDL, IRAF (nebular)
Stellar atmosphere codes (FASTWIND, CMFGEN, WMbasic, TLUSTY)
Photoionization codes (Cloudy, Cloudy3D)

# Qualitative and Quantitative analysis of nebular images.

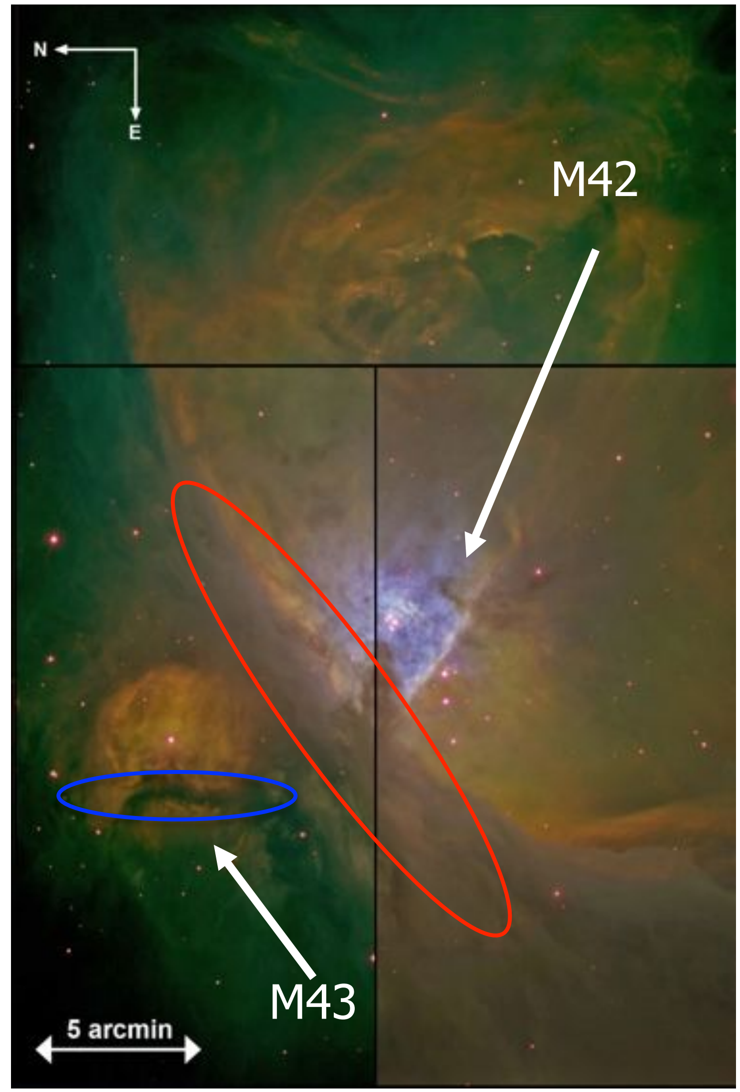
WFC@INT: Hα, [OIII], [SII]



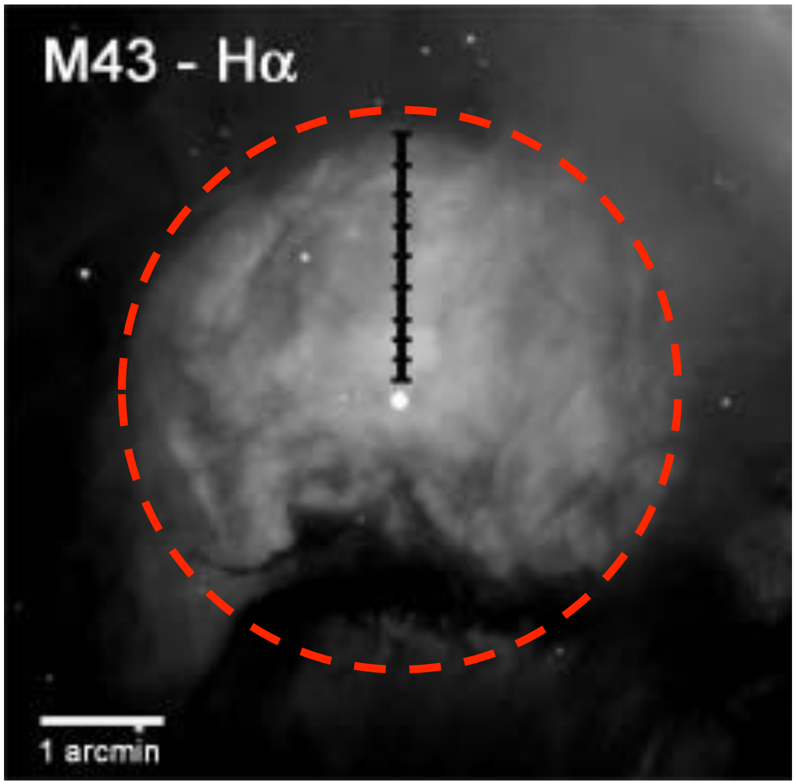

M43 appears as a roundish H II region centered on HD 37061 and well separated from the Orion nebula by the **north-east dust lane.**

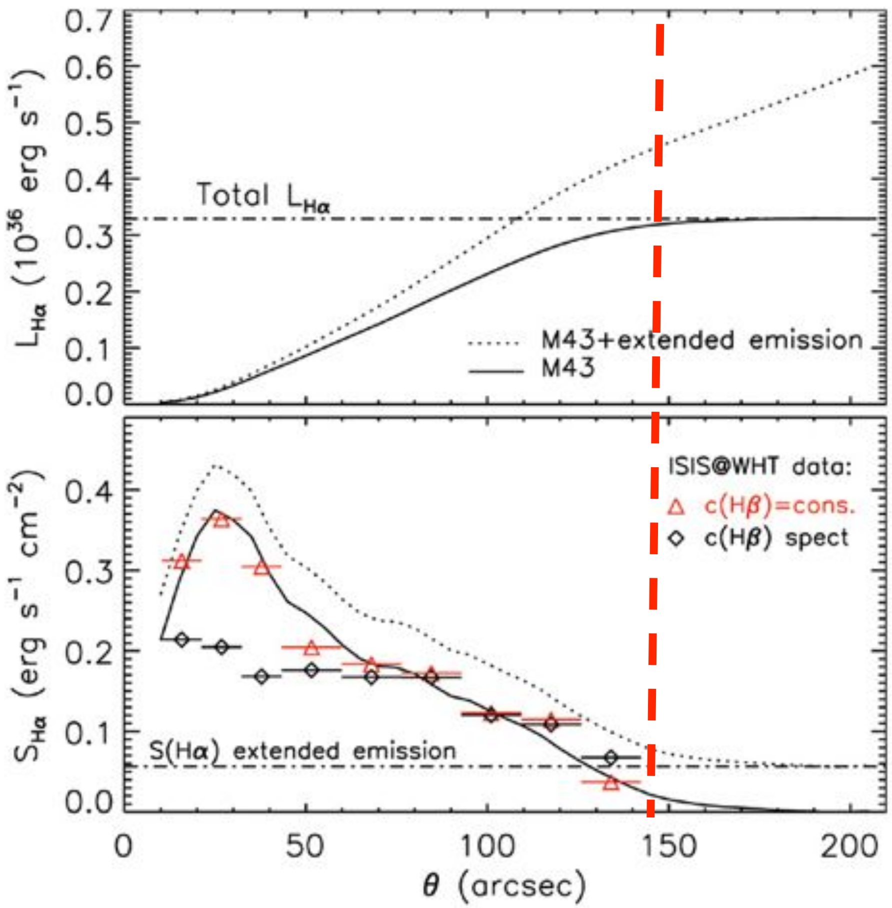
Diameter of about 4.5 arcmin (~0.64 pc assuming a distance of 400 pc).

Crossed by **a dark line** oriented N-S. This dark cloud is located in front of the nebula, blocking the light coming from behind

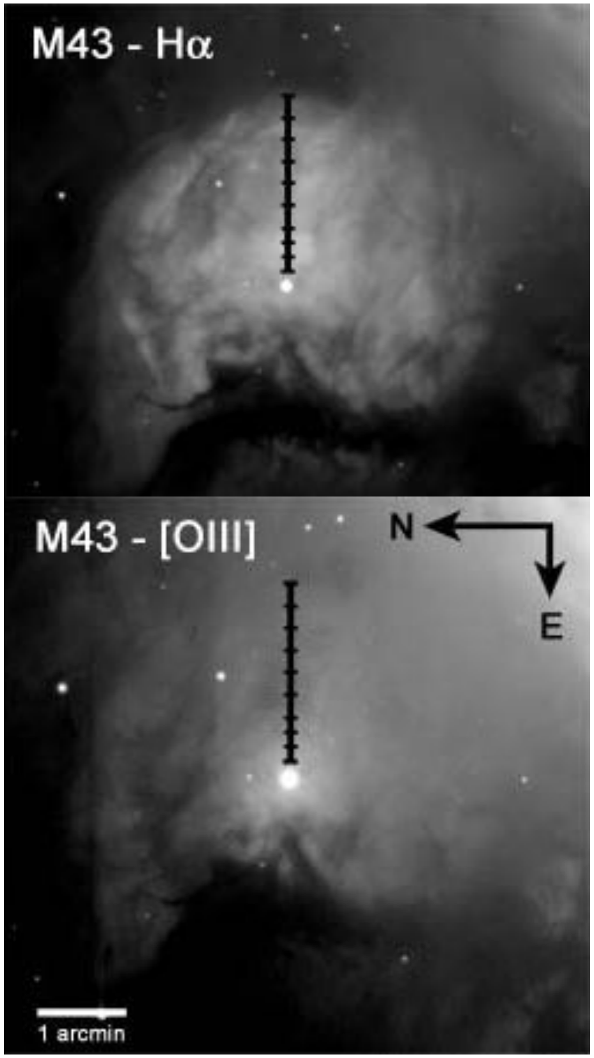


# Qualitative and Quantitative analysis of nebular images.



# Qualitative and Quantitative analysis of nebular images.



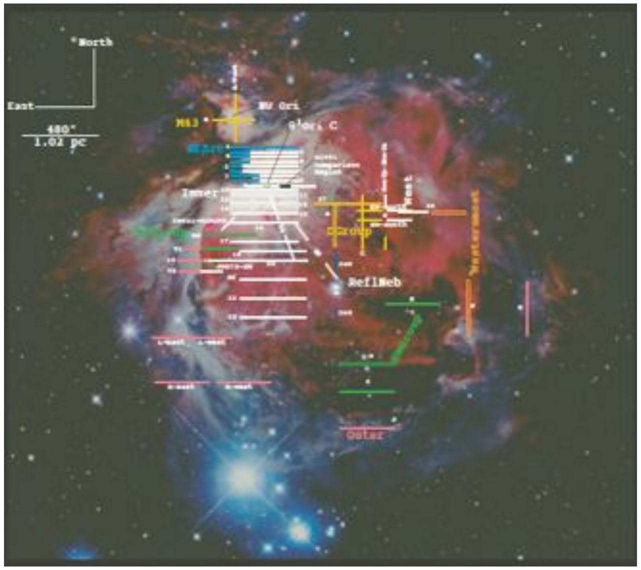

Simple spherical photoionization model with $n_e$=500 cm$^{-3}$ and the SED from the FASTWIND model of the ionizing star.

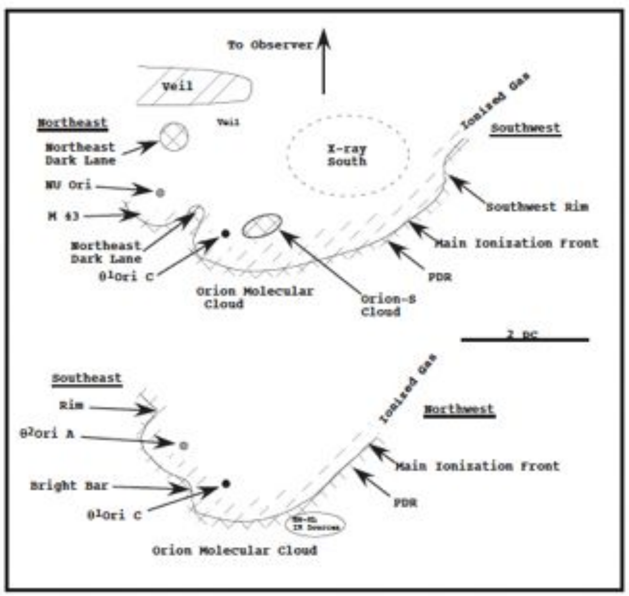
$O^{++}$ region would be ~25 % of the total size of the nebula.

[O III] emission comes from a more extended region, not associated to nebular material ionized by HD~37061

Extended emission

# Qualitative and Quantitative analysis of nebular images. The structure of M43 (and the influence of its "older" sister M42)




O'Dell & Goss (2009)
O'Dell & Harris (2010)

**TALK BY BOB O'DELL YESTERDAY**

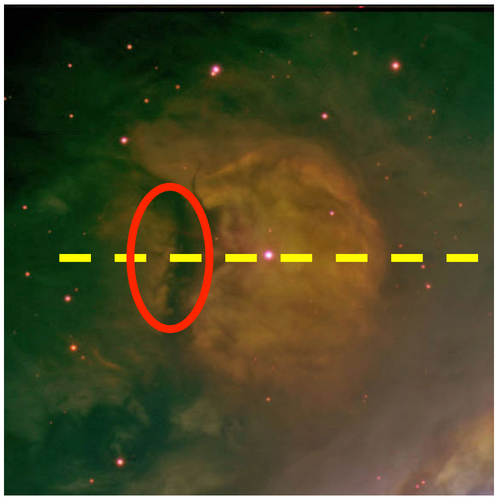
Study of the EON.

Find that scattered light affects physical conditions derived from emission line ratios at distances larger than 5' from the Huygens region. But M43 partially shielded from $\theta^1$Ori C by NE dark lane.

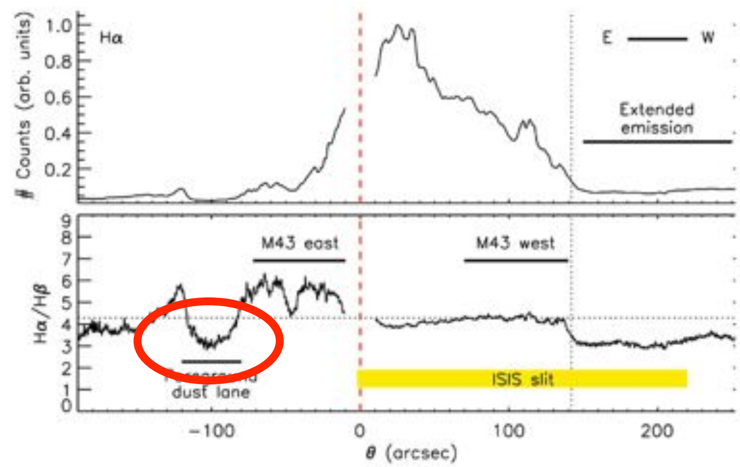
At large distances scattered light becomes dominant.

# Qualitative and Quantitative analysis of nebular images.

## Extinction map

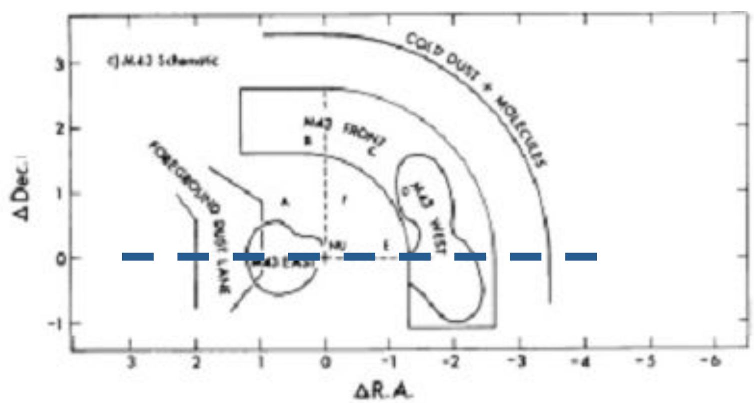


WFC@INT: Hα (+ Hαc, Hβ, Hβc)



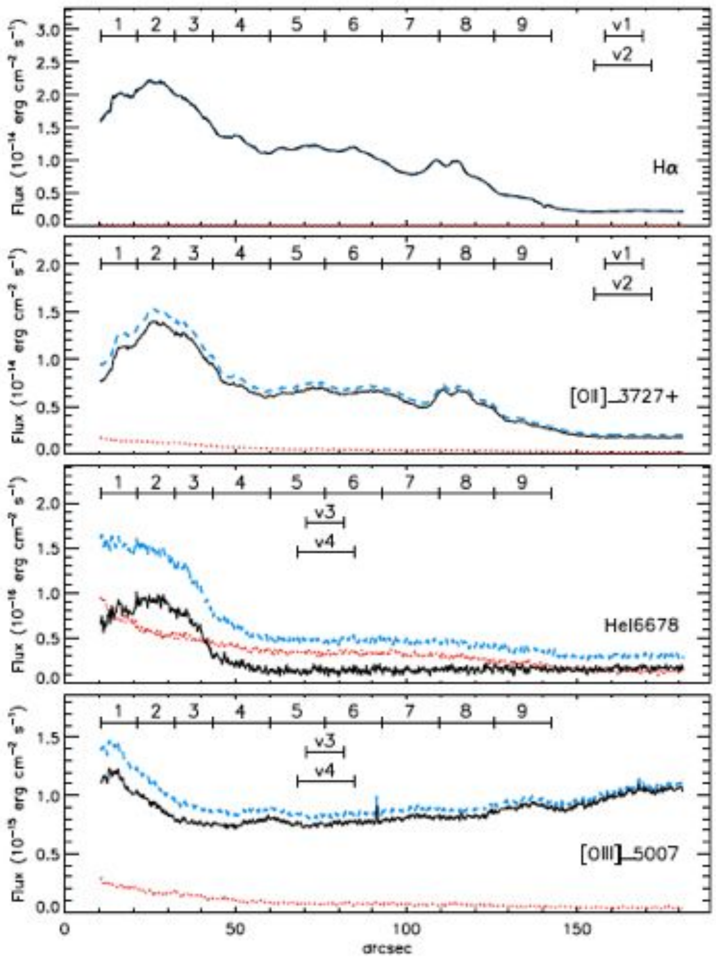

Non constant distribution within the nebula

Low extinction due to observed light is in front of dust lane.



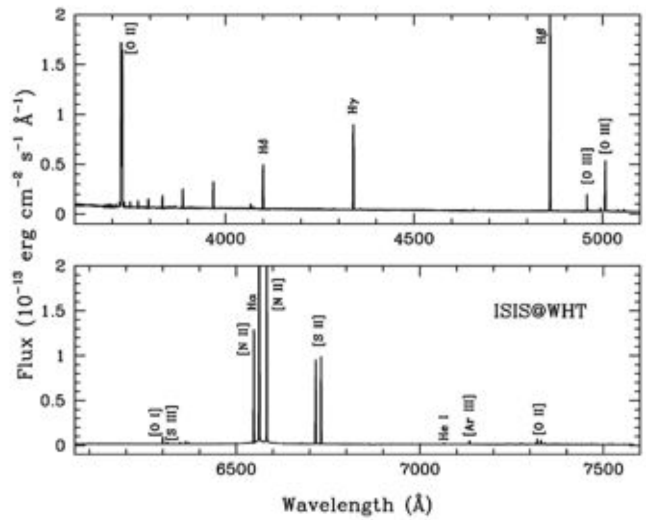

The observed behavior correlates perfectly with the study of dust re-radiation (at 60 $\mu$m) by *Smith et al (1987)*

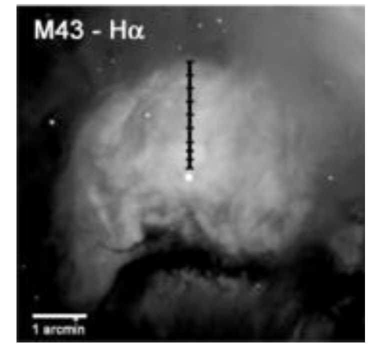
# Empirical analysis of the nebular spectra




ISIS@WHT

R600B: R=7500, 3386-5102 A
R600R: R=8000, 6064-7585 A




9 apertures within the limits of the nebula (θ < 150'')

4 extra apertures at different locations to correct for the extended emission.

# Empirical analysis of the nebular spectra.

## Plasma diagnostics and abundances

Classical approach

$n_e$([S II]), $n_e$([O II])
$T_e$([O II])
$T_e$([O II]) → $T_e$([O III])

Ionic abundances
$He^+$, $O^+$, $O^{++}$, $S^+$, $S^{++}$, $N^+$ and $Ar^{++}$

Total abudances
**O, N and S (no ICFs)**

**Ap #4-7 selected as representative**

| | | | Aperture | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 |
| Center position (arcsec) | | | 15.80 | 26.80 | 37.80 | 51.55 | 68.05 | 84.55 | 101.05 | 117.55 | 134.05 |
| Size (arcsec) | | | 11.0 | 11.0 | 11.0 | 16.5 | 16.5 | 16.5 | 16.5 | 16.5 | 16.5 |
| $\lambda$ (Å) | Ion | Mult. | $I(\lambda)/I(H\beta)$ | | | | | | | | |
| 3726.03 | [O II] | 1F | 93.5±1.8 | 99.7±2.0 | 106±2 | 104±2 | 104±2 | 108±2 | 117±2 | 129±3 | 150±3 |
| 3728.82 | [O II] | 1F | 84.2±1.7 | 91.5±1.8 | 98.1±2.0 | 99.5±2.0 | 98.9±2.0 | 103±2 | 114±2 | 120±2 | 143±3 |
| 3835.39 | H I | H9[2] | 7.50±0.75 | 7.94±0.79 | 8.28±0.83 | 7.91±0.79 | 7.83±0.78 | 7.57±0.76 | 7.98±0.80 | 7.37±0.74 | 7.42±0.74 |
| 4068.60 | [S II] | 1F | 1.58±0.32 | 1.80±0.36 | 1.86±0.37 | 2.43±0.49 | 2.70±0.54 | 3.30±0.66 | 3.84±0.77 | 4.77±0.95 | 5.63±0.56 |
| 4076.35 | [S II] | 1F | 0.64±0.19 | 0.67±0.20 | 0.76±0.23 | 0.74±0.22 | 0.71±0.21 | 1.00±0.30 | 1.16±0.23 | 1.29±0.26 | 1.24±0.25 |
| 4101.74 | H I | Hδ | 26.2±1.3 | 26.2±1.3 | 26.0±1.3 | 25.7±1.3 | 25.6±1.3 | 25.6±1.3 | 25.7±1.3 | 25.6±1.3 | 25.8±1.3 |
| 4340.47 | H I | Hγ | 46.2±2.3 | 46.2±2.3 | 46.5±2.3 | 46.9±2.3 | 46.9±2.4 | 47.0±2.4 | 46.8±2.3 | 46.9±2.4 | 46.8±2.3 |
| 4471.09 | He I | 14 | 1.09±0.22 | 1.35±0.27 | 1.02±0.20 | 0.19±0.08 | – | – | – | – | – |
| 4861.33 | H I | Hβ | 100±2 | 100±2 | 100±2 | 100±2 | 100±2 | 100±2 | 100±2 | 100±2 | 100±2 |
| 4958.91 | [O III] | 1F | 2.52±0.50 | 0.98±0.29 | 0.15±0.06 | – | – | – | 0.93±0.28 | 0.88±0.26 | 7.59±0.76 |
| 5006.94 | [O III] | 1F | 7.86±0.79 | 2.78±0.56 | 0.25±0.10 | – | 0.35±0.14 | 0.13±0.05 | 2.78±0.56 | 3.06±0.61 | 25.42±1.27 |
| 6300.30 | [O I] | 1F | 0.64±0.03 | 0.64±0.03 | 0.60±0.03 | 0.86±0.04 | 1.05±0.05 | 1.30±0.06 | 2.47±0.12 | 3.50±0.17 | 5.39±0.27 |
| 6312.10 | [S III] | 3F | 0.80±0.04 | 0.70±0.03 | 0.69±0.03 | 0.58±0.03 | 0.47±0.02 | 0.42±0.02 | 0.45±0.02 | 0.38±0.02 | 0.36±0.02 |
| 6548.03 | [N II] | 1F | 36.31±1.82 | 38.4±1.9 | 41.3±2.1 | 41.8±2.1 | 42.0±2.1 | 44.2±2.2 | 45.7±2.3 | 50.2±1.0 | 54.1±1.1 |
| 6562.82 | H I | Hα | 292.00±5.84 | 292±6 | 292±6 | 292±6 | 292±6 | 292±6 | 292±6 | 292±6 | 292±6 |
| 6583.41 | [N II] | 1F | 107.12±2.14 | 113±2 | 122±2 | 123±2 | 124±2 | 130±3 | 135±3 | 148±3 | 159±3 |
| 6678.15 | He I | 46 | 1.11±0.06 | 1.13±0.06 | 0.89±0.04 | 0.20±0.01 | – | – | – | 0.03±0.01 | 0.26±0.01 |
| 6716.47 | [S II] | 2F | 18.79±0.94 | 20.2±1.0 | 22.2±1.1 | 25.8±1.3 | 29.4±1.5 | 36.9±1.8 | 42.3±2.1 | 49.1±2.5 | 58.8±1.2 |
| 6730.85 | [S II] | 2F | 20.02±1.00 | 21.4±1.1 | 23.0±1.2 | 26.6±1.3 | 30.4±1.5 | 38.7±1.9 | 42.8±2.1 | 53.3±1.1 | 60.8±1.2 |
| 7065.28 | He I | 10 | 0.92±0.05 | 0.85±0.04 | 0.65±0.03 | 0.15±0.01 | – | – | 0.06±0.01 | 0.09±0.01 | 0.34±0.02 |
| 7135.78 | [Ar III] | 1F | 2.90±0.14 | 2.66±0.13 | 1.70±0.08 | 0.31±0.02 | 0.03±0.01 | 0.03±0.01 | 0.19±0.01 | 0.24±0.01 | 1.16±0.06 |
| 7319.19 | [O II] | 2F | 1.74±0.09 | 1.67±0.08 | 1.67±0.08 | 1.51±0.08 | 1.52±0.08 | 1.66±0.08 | 1.80±0.09 | 2.53±0.13 | 2.67±0.13 |
| 7330.20 | [O II] | 2F | 1.46±0.07 | 1.41±0.07 | 1.34±0.07 | 1.24±0.06 | 1.26±0.06 | 1.39±0.07 | 1.50±0.08 | 2.07±0.10 | 2.20±0.11 |
| $c(H\beta)$ | | | 0.60±0.09 | 0.49±0.08 | 0.51±0.05 | 0.75±0.06 | 0.76±0.06 | 0.79±0.07 | 0.77±0.06 | 0.73±0.06 | 0.99±0.07 |
| $F(H\beta)$ | | | $1.508\times10^{-12}$ | $1.443\times10^{-12}$ | $1.185\times10^{-12}$ | $1.861\times10^{-12}$ | $1.770\times10^{-12}$ | $1.765\times10^{-12}$ | $1.271\times10^{-12}$ | $1.150\times10^{-12}$ | $7.131\times10^{-13}$ |
| $n_e$([O II]) | | | 560±50 | 520±50 | 500±40 | 440±40 | 450±40 | 450±40 | 420±40 | 510±50 | 460±40 |
| $n_e$([S II]) | | | 650±170 | 630±170 | 570±160 | 560±150 | 560±150 | 600±160 | 520±150 | 690±140 | 580±60 |
| $T_e$([O II]) | | | 7850±160 | 7600±150 | 7360±140 | 7260±130 | 7270±140 | 7420±140 | 7440±140 | 8070±180 | 7810±180 |
| $T_e$([O III])[3] | | | 7360±1700 | 7000±1650 | 6660±1600 | – | – | – | – | – | – |
| $He^+/H^+$ | | | 10.44±0.02 | 10.45±0.03 | 10.34±0.03 | – | – | – | – | – | – |
| $O^+/H^+$ | | | 8.34±0.05 | 8.45±0.05 | 8.55±0.05 | 8.58±0.05 | 8.58±0.05 | 8.54±0.05 | 8.57±0.05 | 8.42±0.05 | 8.56±0.06 |
| $O^{2+}/H^+$ | | | 6.97±0.20 | 6.64±0.22 | 5.83±0.26 | – | – | – | – | – | – |
| $N^+/H^+$ | | | 7.63±0.04 | 7.70±0.04 | 7.78±0.04 | 7.80±0.04 | 7.80±0.04 | 7.80±0.04 | 7.81±0.04 | 7.73±0.04 | 7.81±0.04 |
| $S^+/H^+$ | | | 6.28±0.04 | 6.35±0.04 | 6.43±0.04 | 6.51±0.04 | 6.56±0.04 | 6.64±0.04 | 6.68±0.04 | 6.66±0.04 | 6.77±0.04 |
| $S^{2+}/H^+$ | | | 6.78±0.04 | 6.80±0.04 | 6.87±0.04 | 6.83±0.04 | 6.73±0.04 | 6.64±0.04 | 6.66±0.04 | 6.39±0.05 | 6.44±0.05 |
| $Ar^{2+}/H^+$ | | | 5.79±0.16 | 5.82±0.17 | 5.69±0.17 | – | – | – | – | – | – |
| O/H | | | 8.36±0.05 | 8.45±0.05 | 8.55±0.05 | 8.58±0.05 | 8.58±0.05 | 8.54±0.05 | 8.57±0.05 | 8.42±0.05 | 8.56±0.06 |
| N/H | | | 7.65±0.08 | 7.71±0.08 | 7.78±0.08 | 7.80±0.04 | 7.80±0.04 | 7.80±0.04 | 7.81±0.04 | 7.73±0.04 | 7.81±0.04 |
| S/H | | | 6.90±0.04 | 6.93±0.03 | 7.01±0.03 | 7.00±0.03 | 6.96±0.03 | 6.94±0.03 | 6.97±0.03 | 6.85±0.03 | 6.94±0.03 |

[1] The errors in the line fluxes refer only to uncertainties in the line measurements (see text). $F(H\beta)$ in erg $cm^{-2}s^{-1}$; $n_e$ in $cm^{-3}$; $T_e$ in K; ionic abundances in log $(X^{+i}/H^+) + 12$.
[2] Blended with He I λ3833.57 line.
[3] $T_e$([O III]) obtained using the empirical relation between $T_e$([O II]) and $T_e$([O III]) obtained from the data by García-Rojas & Esteban (2007) (see text).

# Empirical analysis of the nebular spectra.

## O, S and N abundances. Results and comparison with M42 abundances.

| Element | M 43 | M 42 (GRE07) | M 42 (SDS10) |
|---|---|---|---|
| O | 8.57±0.05 | 8.54±0.03 | 8.52±0.01 |
| S | 6.97±0.03 | 7.04±0.04 | 6.87±0.04 |
| N | 7.80±0.04 | 7.73±0.09 | 7.90±0.09 |

M43: No ICF correction needed

M42: GRE07 (García-Rojas & Esteban 2007) Use empirical ICFs for N and S. Same atomic data set than in M43

M42: SDS10 (Simón-Díaz & Stasińska 2010) Use photoionization model ICFs for N and S. Atomic data in S are different.

# Empirical analysis of the nebular spectra.

## Importance of an adequate correction of the scattered light component

| | | Uncorrected | | Corrected | | Uncorrected |
|---|---|---|---|---|---|---|
| | | A4 | A5 | A4 | A5 | Total Slit |
| $n_e$(cm$^{-3}$) | [O II] | 475 | 485 | 440 | 450 | 510 |
| | [S II] | 560 | 565 | 560 | 560 | 600 |
| $T_e$(K) | [O II] | 7650 | 7700 | 7260 | 7270 | 7900 |
| | [O III] | — | — | — | — | 7450 |
| $\epsilon(X^{+i})$ | $O^+$ | 8.45 | 8.44 | 8.58 | 8.58 | 8.38 |
| | $O^{++}$ | — | — | — | — | 7.45 |
| | $N^+$ | 7.71 | 7.70 | 7.80 | 7.80 | 7.66 |
| | $S^+$ | 6.42 | 6.46 | 6.51 | 6.56 | 6.42 |
| | $S^{++}$ | 6.77 | 6.70 | 6.83 | 6.73 | 6.69 |
| | $Ar^{++}$ | — | — | — | — | 5.64 |
| $\epsilon(X)$ | O | 8.50 | 8.49 | 8.58 | 8.58 | 8.43 |
| | N | 7.75 | 7.75 | 7.80 | 7.80 | 7.71 |
| | S | 6.93 | 6.90 | 7.00 | 6.96 | 6.88 |

(1) $T_e$, ionic, and total abundance values are based on the assumption $n_e$=$n_e$([O II]) as discussed in Sect. 5.6.

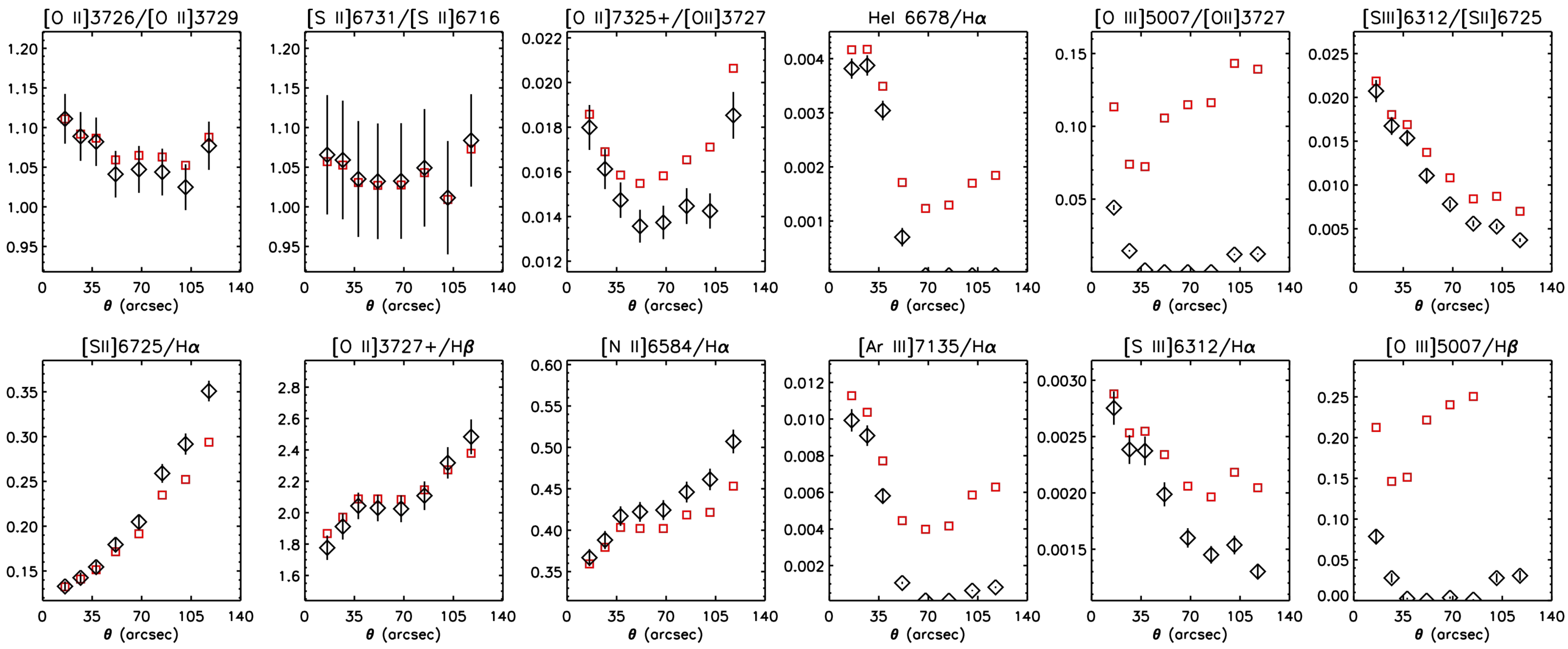
M42

*Esteban et al. (2004)*

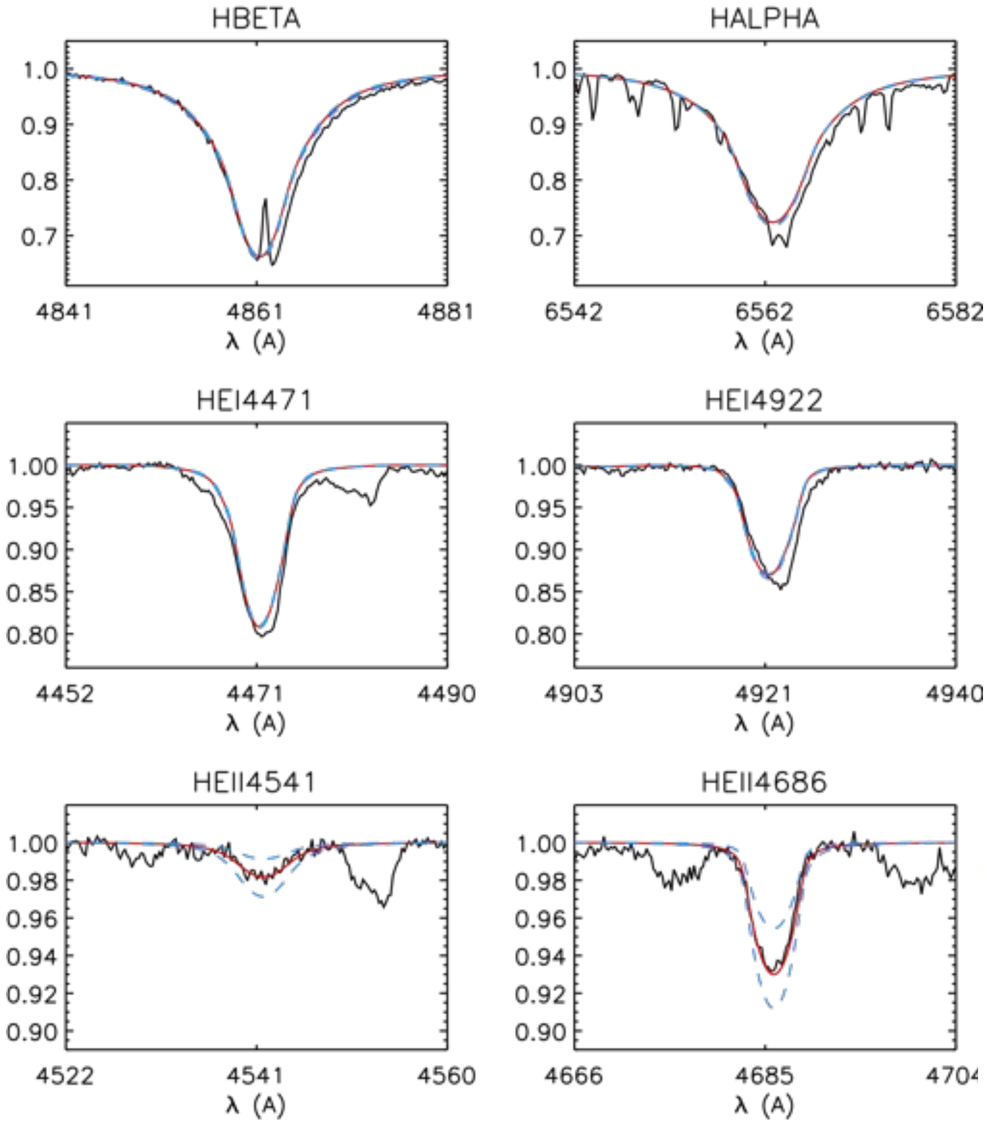
| CEL | ORL |
|---|---|
| 8.54 | 8.65 (±0.03) |

# M43: Towards a tailored photoionization model (on-going work)

Spatial distribution of nebular line ratios will be used to constraint the nebular $n_e$, $T_e$, ionization structure & abundances



# Quantitative spectroscopic analysis of HD 37061




IDS@INT

H2400B: R=8000, 4060-4590 A
H2400B: R=8000, 4550-5070 A
H1800V: R=10000, 6090-6760 A

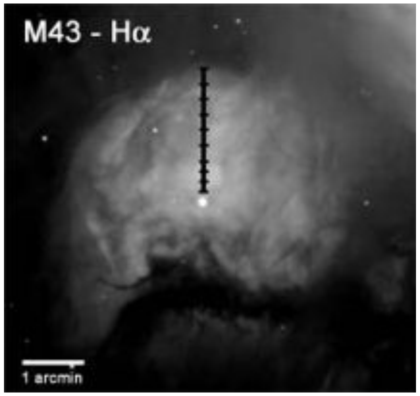
Stellar parameters obtained using FASTWIND

Standard techniques:

- *v* sin*i* = 200 km/s
- FASTWIND stellar atmosphere code
- H + He I/II lines
- d=400 ± 50 pc
- mv=6.84, Av=2.09 → Mv=-3.3 ± 0.3

| | | | |
|---|---|---|---|
| $T_{\rm eff}$(K) | $31000 \pm 500$ | R ($R_\odot$) | $5.7 \pm 0.8$ |
| log $g$(dex) | $4.2 \pm 0.1$ | log$L/L_\odot$ | $4.42 \pm 0.12$ |
| $\epsilon$(He) | 0.09 (assumed) | M ($M_\odot$) | $19 \pm 7$ |
| log Q | -15 (assumed) | log Q($H^0$) | $47.2 \pm 0.2$ |

# Qualitative and Quantitative analysis of nebular images.




d= 400 ± 50 pc

(Hα) = 4 x L(Hα) MW-SW quadrant

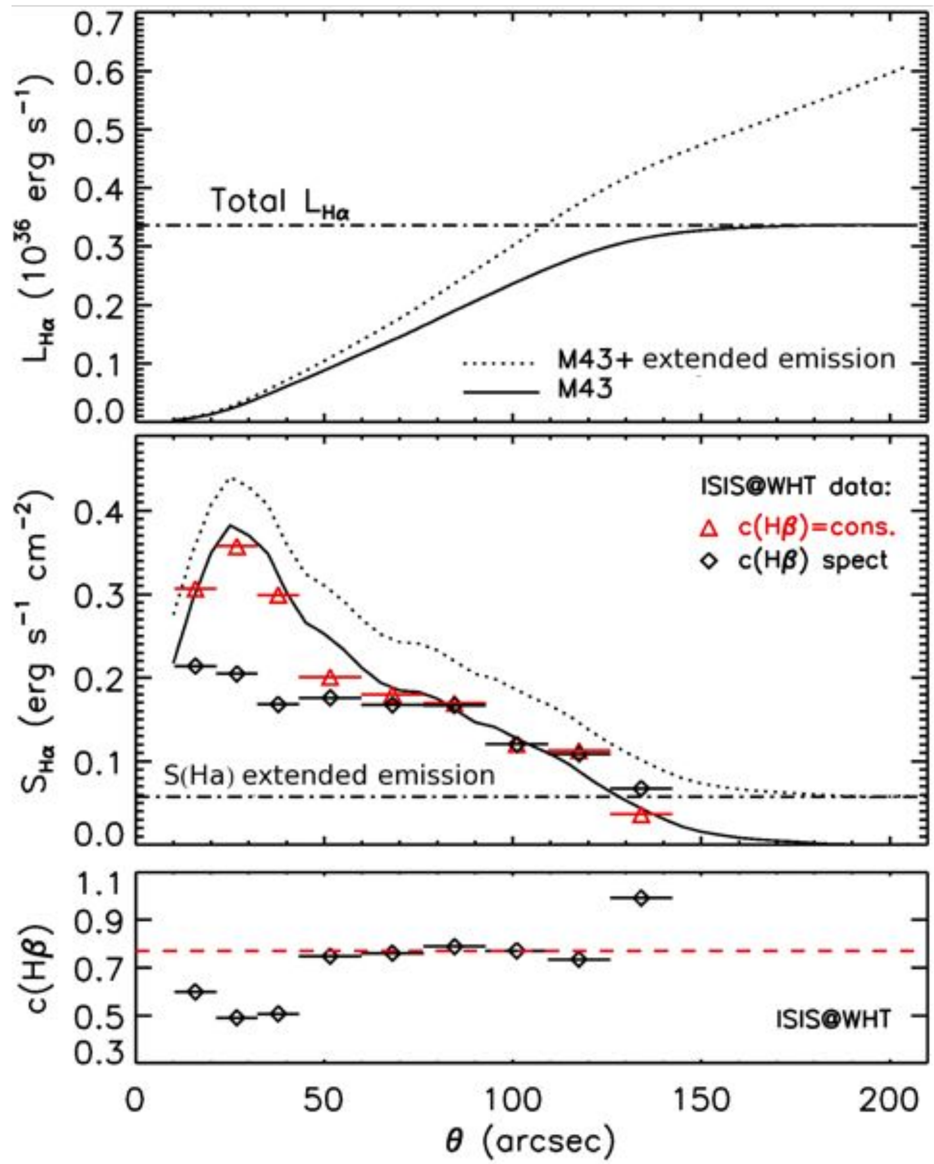
Corrected for [NII] contribution

Non constant c (Hβ)

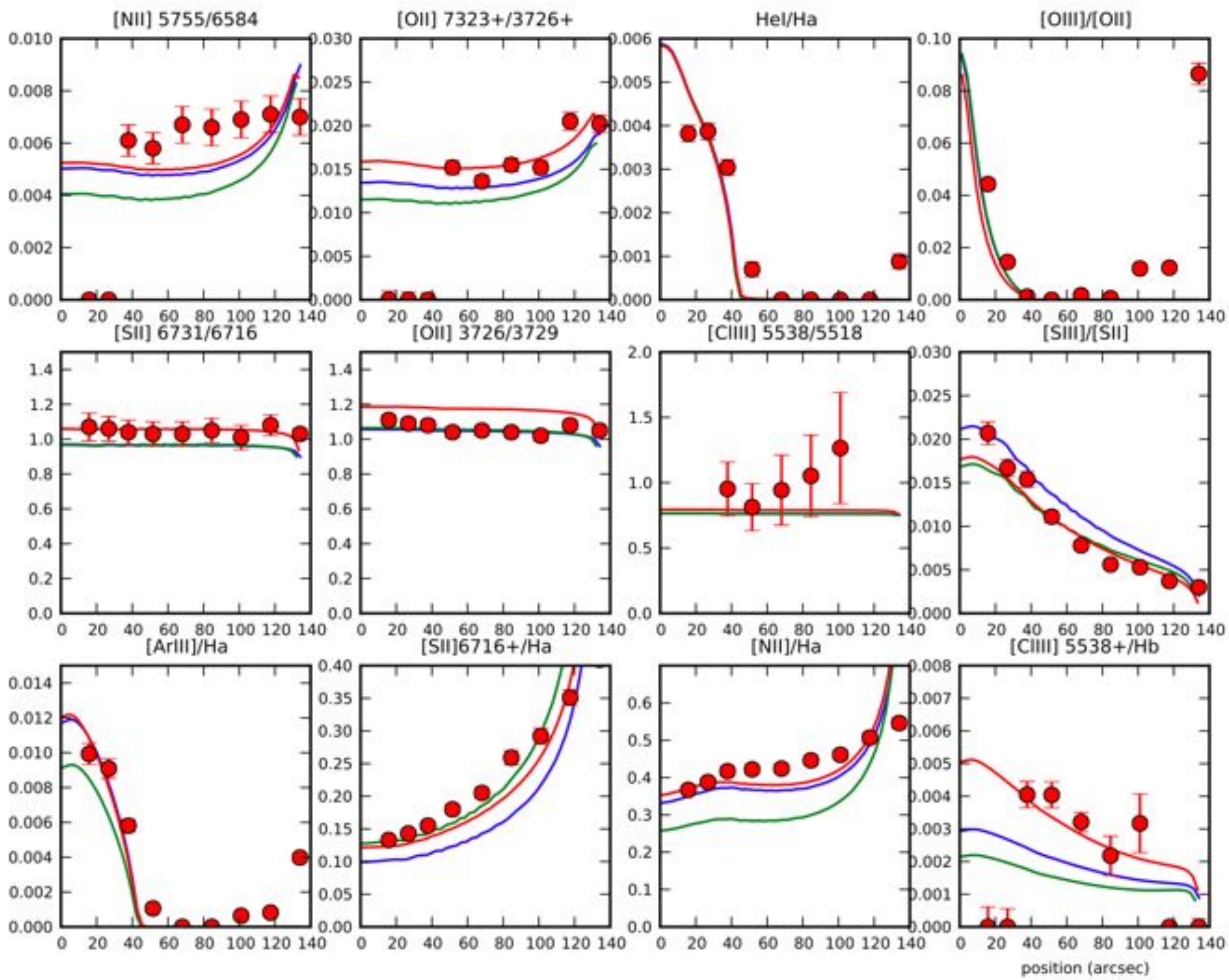
$(L_{H\alpha})_{corr} = (3.0\pm1.1)\times10^{35}$ erg s$^{-1}$

$Q(H^0) \rightarrow L_{H\alpha} = (2.5\pm1.0)\times10^{35}$ erg s$^{-1}$

A (mostly) ionized bounded nebula



# Work in progress: Photoionization models




Blue: O, N, S abundances from M43. Other elements from Esteban et al. (2004)

Green: S/H increased

Red: S/H and Cl/H increased. Density increased. Filling factor=0.5

# To take away…

✓ We present a combined and comprehensive study of the nebula and its ionizing star by using as many observational constraints as possible.

✓ Even the simple HII regions are not so simple when studied in detail
  → scattered light, non constant extinction

✓ Mind the atomic data and ICFs you use in your nebular analyses
  → their effect on the nebular abundances is non negligible

✓ What are the "real" abundances in the nebula? (here we only have CELs…)
  → but this is not the end of the story

**Stay tunned!!!**
**We're still working on it**

# Dziękuję Bardzo