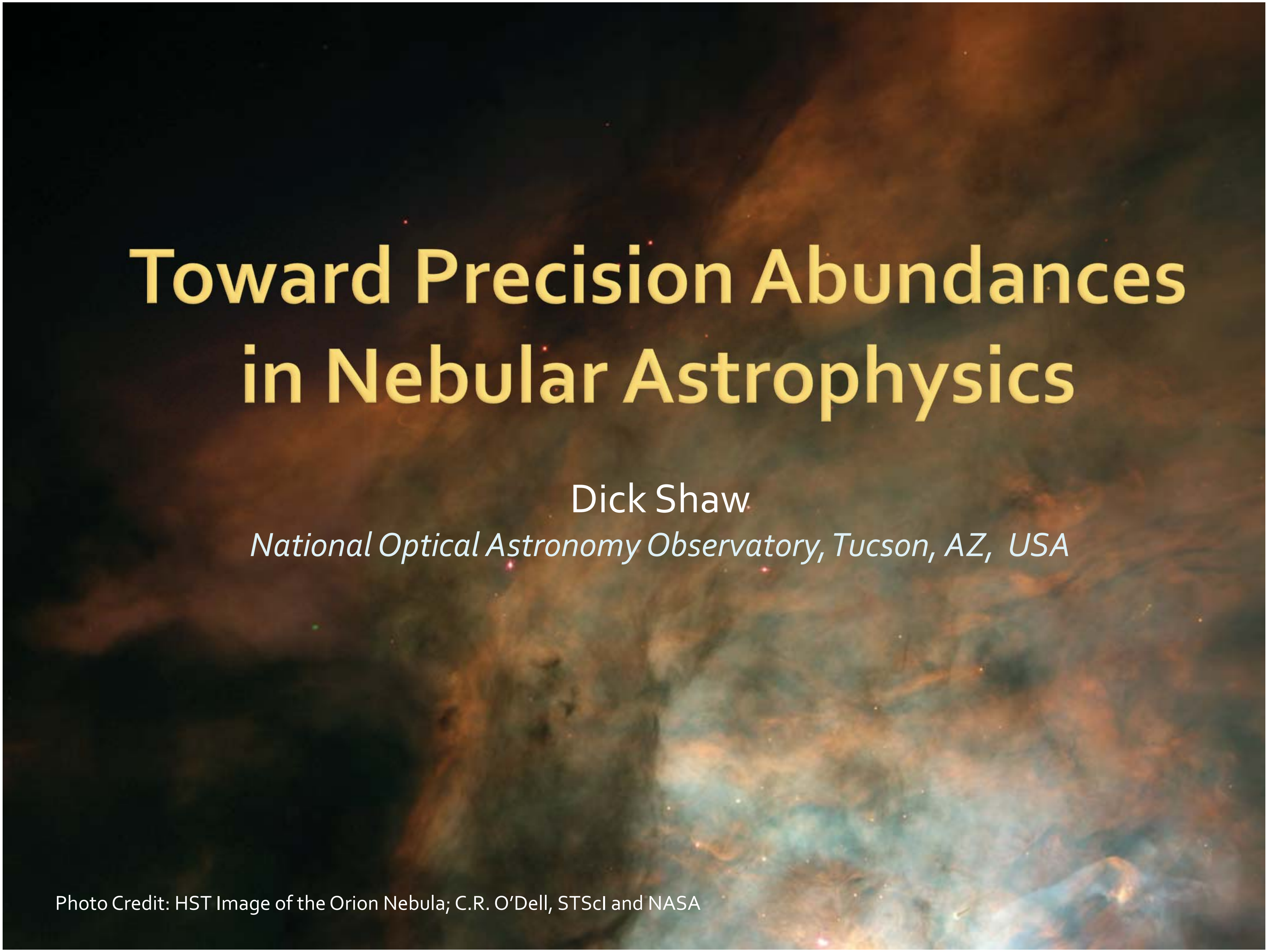

# Toward Precision Abundances in Nebular Astrophysics

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Photo Credit: HST Image of the Orion Nebula; C.R. O'Dell, STScI and NASA

# Introduction

Chemical abundances from astrophysical objects provide key evidence to support our understanding of the Universe and the physical processes that operate. Abundances from nebulae in various contexts (e.g., star forming regions, active galaxies, planetary nebulae, the ISM) have been derived for decades. However, well developed theory and simulation now demand greater accuracies than are often realized in order to address fundamental questions.

Are our current observations, techniques, and atomic data up to the task?

It is time to assess the limitations of our approaches, and to quantify with greater care the uncertainties in the chain of analysis that leads from spectroscopic observations to elemental abundances.

# Sources of Uncertainty

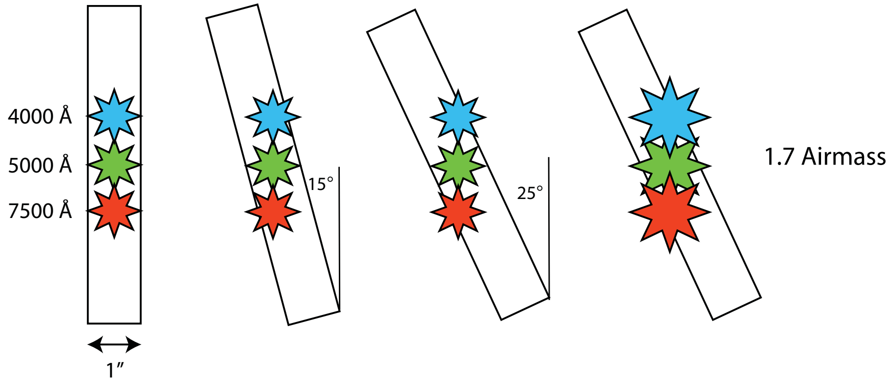
*Uncertainties* and *systematic errors* enter in many places to the chain of analysis that leads to elemental abundances. Here are some common ones:

- **Observations**
  - Experimental design
  - Accuracy
- Input Physics: what do we include, how well is it modelled?
  - Model of $T_e$ vs. I.P., density profile, $t^2$
  - Assumed source function, radiative transfer effects
  - Ionization/Recombination vs. collisional excitation, shocks
  - Accounting for charge exchange, dielectronic recombination, etc.
- **Ionization Correction Factors (ICFs)**
  - Need to distinguish between *unobserved* vs. *undetected* emission
- Atomic Data

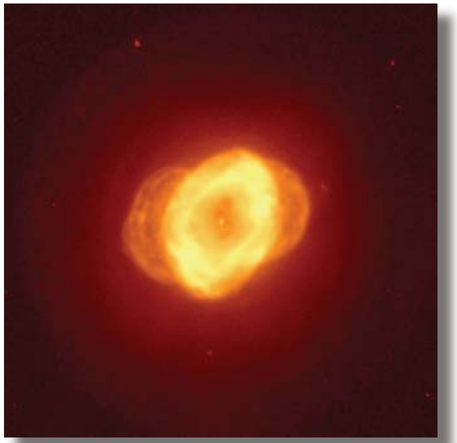
# Sources of Error

## Experimental Design Issues

- Spectral resolution & coverage
  - Ionization stages in UV, Vis, IR
  - Need to resolve critical lines
- Atmospheric dispersion
  - Requires rotator or compensator
  - Slit losses result in steepened Balmer decrements, color-dependent flux errors
- Placement of aperture
  - Extended, complex targets
  - Ionization fractionation
- Scattered light
  - Faint halos surrounding PNe



NGC 6302

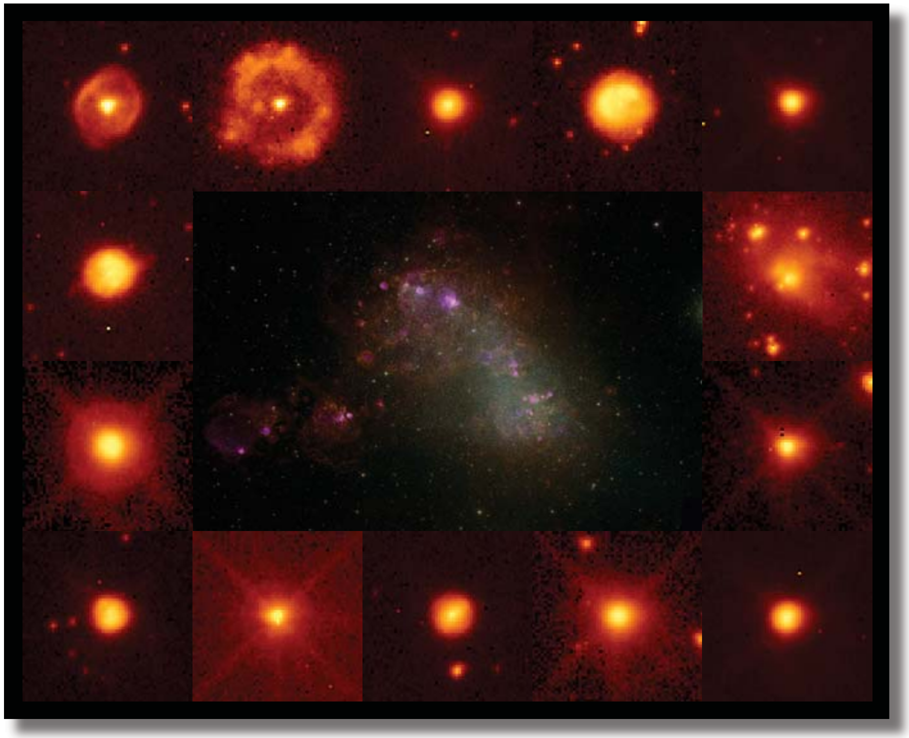


PN-G053.3+24.0

# Case Study: SMC Planetary Nebulae

I will illustrate some of the issues of deriving accurate nebular abundances by reviewing our recent analysis of emission lines of 14 PNe in the Small Magellanic Cloud.

- Used “direct methods”
- Abundances of He, N, O, Ne, S, & Ar
- Compared to multiple published abundance studies
- Analyzed veracity of ICFs



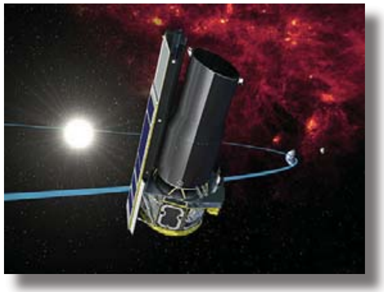
Shaw, et al. 2010, ApJ, 717, 562

# A Rare Opportunity

The SMC PN sample presents an unusual opportunity to assess the magnitude of uncertainties in most stages of the abundance analysis.

All targets:

- are in the same part of the sky
- are angularly small
- have spectra from 2 or more of:
    - *HST*/STIS or IUE 120—300 nm
    - NTT/EMMI long-slit, echelle 370—740 nm
    - *Spitzer* IRS 5—40 µm
- have low interstellar extinction
- have uncomplicated structure
- no complicated backgrounds



Spitzer/IRS

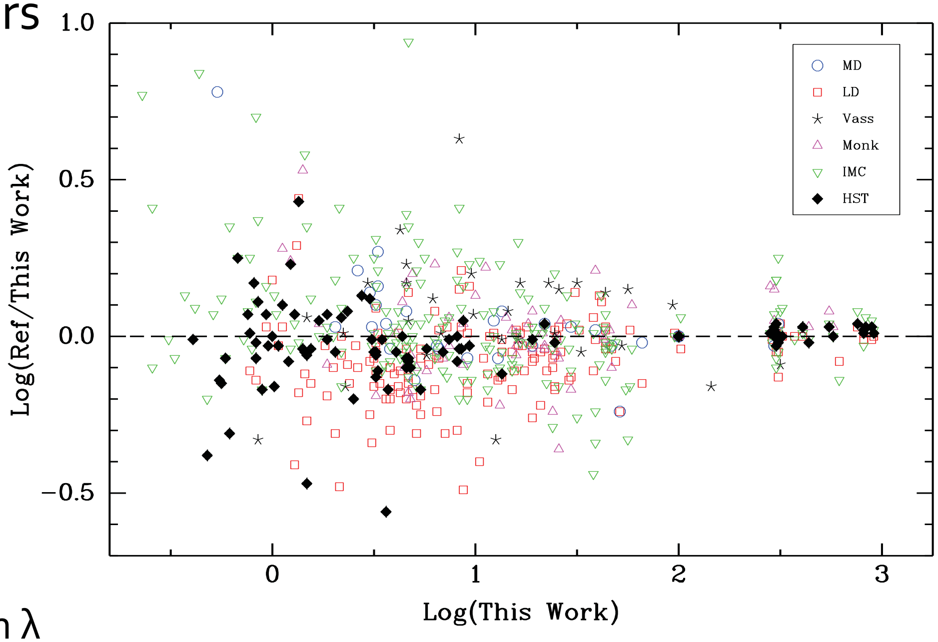
NTT/EMMI

HST/STIS

# Data Comparison

## Step 1: compare emission line intensities from literature

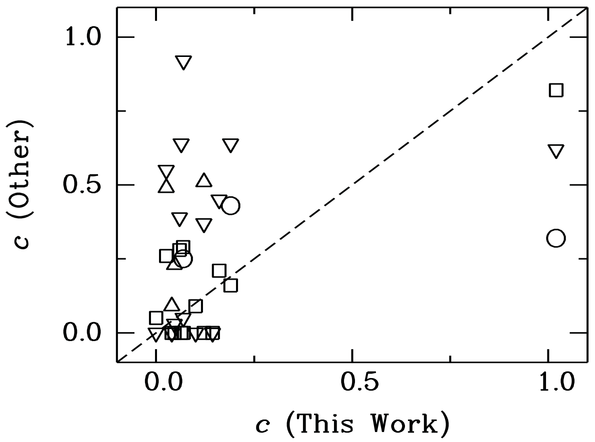
- Large discrepancies among authors
  - Larger than quoted errors (5—50%)
  - Trends with intensity & λ
- Key comparisons:
  - Ground & space-based intensities
  - Balmer decrement
  - Sanity checks: I(5007)/I(4959), etc.
  - Consistent ionic abundances from different emission lines
- Accurate abundances require:
  - Excellent calibration over wide range in λ
  - High dynamic range
  - Good resolution (a few thousand)

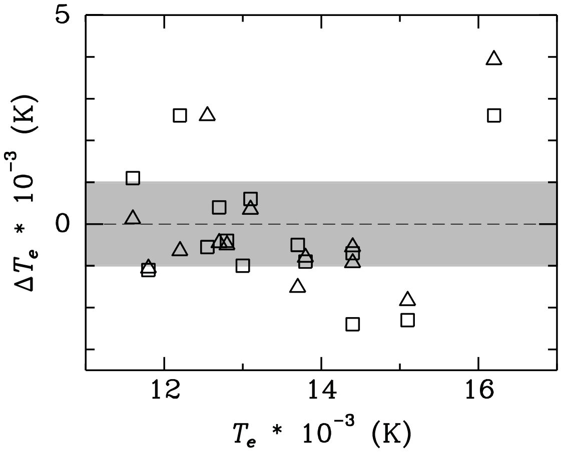


# Diagnostics Comparison

## Step 2: compare diagnostics

- Most physical diagnostics derived from ratios w/faint lines
  - $T_e$ from [O III], [S III], [N II]
  - $N_e$ from [S II], [Cl III], [Ar IV]
- Indicators of accuracy
  - Balmer decrement: slit losses➔too steep
  - For a given ion, agreement from different transitions
    - [O II] I(3727)/I(7325), etc.
- Consider uncertainties
  - Important that uncertainties in $T_e$ and $N_e$ be propagated to uncertainties in abundances (optical/UV: exponential dependence on $T_e$ ; IR: dependence on $N_e$)
  - Inaccuracies in $T_e$ of 1000 K result in abundance discrepancies of ~0.1 dex

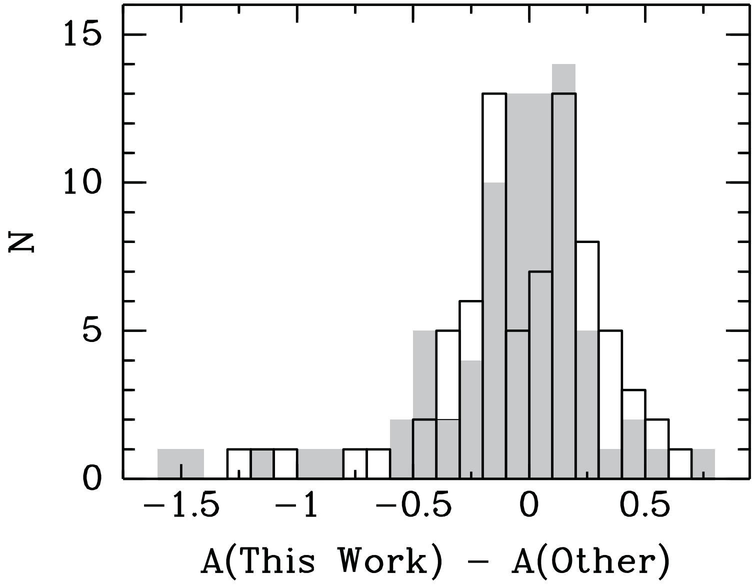




# Abundance Comparison

## Step 3: compare elemental abundances

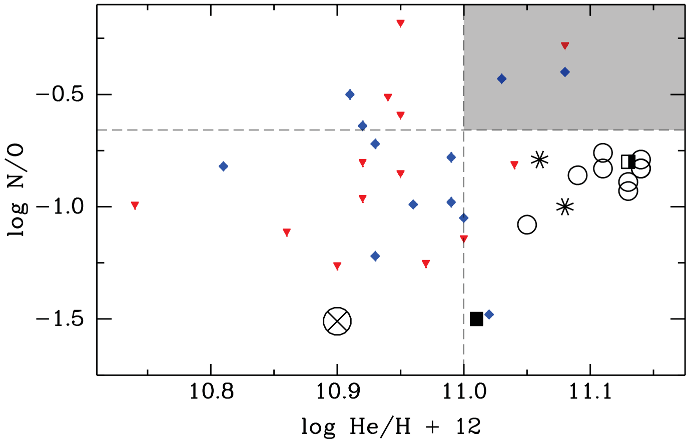
- The discrepancies between two large surveys and ours are quite large
  - Width is >0.15 dex (40%); tails to 1.5 dex
  - Largest discrepancies come from weakest lines, where others used arbitrary $T_e$ & $N_e$
- It is often not possible to compare ionic abundances
  - Usually the same ICF recipes are used: Kingsburgh & Barlow (1994)
- Adopted atomic data are not often cited in literature

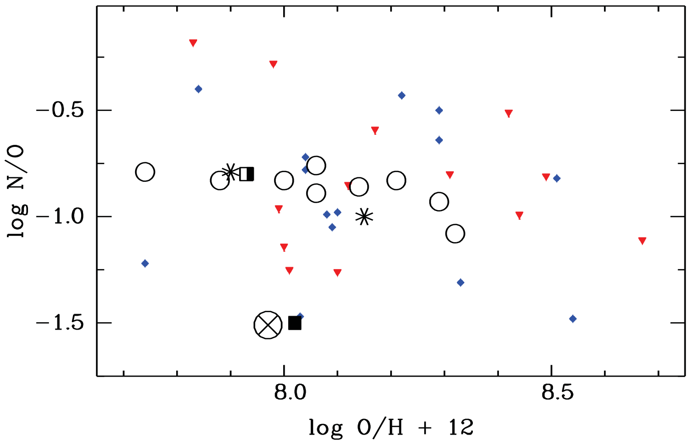


Conclusion: abundance discrepancies result from both non-linear contributions to the error budget and systematic errors.

# Impact of Abundance Accuracy

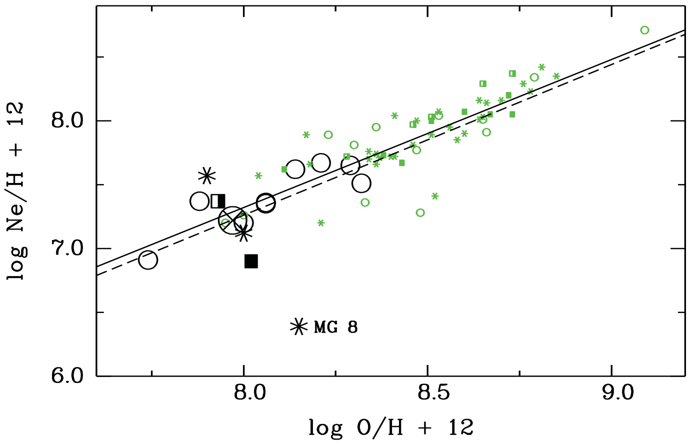
- Some Expectations:
  - Enrichments of some elements: He, C, N
  - Little change expected for O, Ne, S, Ar
- Results:
  - Dispersion in the distribution is much higher for literature abundances than ours
  - Scientific interpretation is different as well, although our sample is small
    - Leisy & Dennefeld (2006) claim that Type-I vs. Type-2 PNe are not well segregated, implying that there is no sharp cut-off mass for AGB stars that experience hot-bottom burning; Shaw et al. (2007) find no Type-I PNe.
    - LD06 also claim some evidence for O-N cycle; we find no evidence of that.
  - One target (SMP11) appears to be a compact HII region, rather than a PN

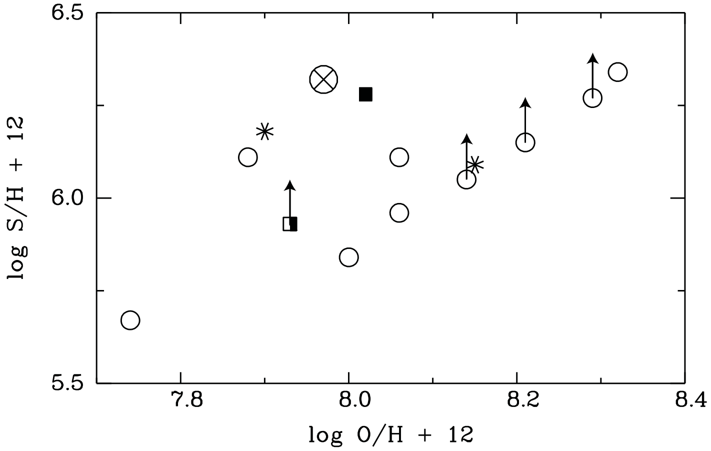




# Impact of Abundance Accuracy

- More Results:
  - O and Ne abundances appear to change in lock-step, and show no evidence for enrichment during AGB evolution for stars in this mass range.
  - The ICFs for some elements (O, Ne, S) were found to be mostly accurate
    - Compared optical * ICF(X) vs. optical + IR
    - Discrepancies only for the PNe with the highest ionization
  - The “sulfur anomaly” (Henry et al. 2004) appears to be genuine
    - Could problematic atomic data play a role?
    - New S atomic data will be installed soon( Tayal et al. 2010)
  - Abundance of Ne$^{2+}$ from optical are 50% weaker than those derived from IR
    - Problem with atomic data?





# Breakdown of Errors

| Source of Error | Range of Uncertainty | Strategy for Improvement |
|---|---|---|
| Fluxes | 3—300% | Improved observing technique; more & deeper spectra |
| $T_e$ $N_e$ $c$ | 10—100% | Improved fluxes, better analysis, account for variations in $T_e$ |
| ICFs | 10—300% | Broader wavelength coverage (e.g., satellite UV, IR); modelling |
| Atomic Data | 10—100% ?? | More detailed computations, laboratory work, feedback from observations |
| **Total** | 10—1000% | All of the above, plus rigorous error analysis |

This is one view of the abundance accuracy issues. This workshop is a good opportunity to embellish and refine the above list.

# Future Challenges

Where do we go from here? I offer the following thoughts:

- Accuracy of current generation nebular abundances leaves much room for improvement.
- It is possible to achieve observational accuracy of ~10%, but this may not often be realized.
- Uncertainties in atomic data could be a limiting factor for accuracy. It would help to quantify better the effects of adopting new atomic data on abundance analysis.
- Systematic problems with absolute abundances, or even the spread of a distribution among targets, can dramatically affect scientific interpretations

Here are some questions to ponder during this workshop:

- What accuracies are required of nebular abundance analysis to make progress in particular areas of science? (I argue that 10% or better is needed in at least some areas.)
- Is it possible to better quantify the uncertainties in atomic data?
  - As a function of ion, parameter, etc.
- Can the pundits find a way to routinely and accurately quantify the effects of adopting new atomic data on abundance analysis?