

# An empirical calibration of nebular abundances based on the sulphur emission lines

Angeles I. Díaz and Enrique Pérez-Montero

*Dpto de Física Teórica, C-XI, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

Accepted 1999 September 15. Received 1999 July 12; in original form 1999 February 22

## ABSTRACT

We present an empirical calibration of nebular abundances based on the strong emission lines of [S II] and [S III] in the red part of the spectrum through the definition of a sulphur abundance parameter  $S_{23}$ . This calibration presents two important advantages against the commonly used one based on the optical oxygen lines: it remains single-valued up to abundances close to solar and is almost independent of the degree of ionization of the nebula.

**Key words:** ISM: abundances – ISM: general – H II regions – galaxies: abundances.

## 1 INTRODUCTION

The analysis of nebular spectra constitutes the best, and in some cases the only, method for the determination of chemical abundances in spiral and irregular galaxies, as well as in sites of recent star formation. The abundances of several elements like He, O, N and S can in principle be determined, because strong emission lines of these elements, some of them in their dominant ionization states, are present in the optical region of the spectrum. This requires knowledge of the electron temperature, which can be obtained by measuring appropriate line ratios like [O II]  $\lambda 4363/(\lambda 4959 + \lambda 5007)$ , [N II]  $\lambda 5755/(\lambda 6548 + \lambda 6584)$ , [O II]  $\lambda 7327/(\lambda 3727 + \lambda 3729)$  or [S III]  $\lambda 6312/(\lambda 9069 + \lambda 9532)$ .

Unfortunately, these line ratios usually involve one intrinsically weak line, which can be detected and measured with confidence only for the brighter and hotter objects, and in many cases – distant galaxies, low surface brightness objects, relatively low-excitation regions – they become too faint to be observed.

In these cases, an empirical method based on the intensities of the easily observable optical lines is widely used. The method, originally proposed by Pagel et al. (1979) and Alloin et al. (1979), relies on the variation of these lines with oxygen abundance. Pagel et al. (1979) defined an abundance parameter  $R_{23} = ([\text{O II}]\lambda 3727 + [\text{O III}]\lambda 4959 + \lambda 5007)/\text{H}\beta$ , which increases with increasing abundance for abundances lower than about 20 per cent solar, and then reverses its behaviour, decreasing with increasing abundance, because above this value a higher oxygen abundance leads to a more effective cooling, the electron temperature becomes lower and the optical emission lines become weaker.

In principle, the calibration of the  $R_{23}$  versus oxygen abundance relation can be carried out empirically in the low metallicity regime where electron temperatures can be derived directly, but requires the use of theoretical models for the so-called high-abundance branch. Several different calibrations have been made (Edmunds & Pagel 1984; McCall, Rybski & Shields 1985; Dopita & Evans 1986; Skillman 1989; McGaugh 1991) as more

observational data and more improved models have become available. However, two problems that are difficult to solve still remain. The first one is related to the two-valued nature of the calibration, which can lead to important errors in the derived abundances. The second one concerns the dependence of  $R_{23}$  on the degree of ionization of the nebula (see Skillman 1989).  $R_{23}$  also depends on density, but this can be considered as a second-order effect for low-density regions ( $n_{\text{H}} \approx 100 \text{ cm}^{-3}$ ), which constitute the majority of the extragalactic population. These two facts, taken together, produce a large dispersion of the data for values of  $\log R_{23} \geq 0.8$  and  $12 + \log(\text{O}/\text{H}) \geq 8.0$ , with objects with the same value of  $\log R_{23}$  having actual abundances that differ by almost an order of magnitude. Unfortunately, a significant number of objects (about 40 per cent of the observed H II galaxies; Díaz, 1998) have  $\log R_{23} \geq 0.8$ , for which the calibration is most uncertain, and this percentage is even higher for H II regions in normal spiral galaxies.

Here we present an alternative abundance calibration based on the intensities of the sulphur lines: [S II]  $\lambda 6716$ ,  $\lambda 6731$  and [S III]  $\lambda 9069$ ,  $\lambda 9532$ , through the use of the sulphur abundance parameter  $S_{23}$  (Vílchez & Esteban 1996).

Spectroscopically, these lines are analogous to the optical oxygen lines defining  $R_{23}$  but, because of their longer wavelengths, their contribution to the cooling of the nebula should become important at a somewhat lower temperature. Despite this, the lower abundance of sulphur makes these lines less significant than the [O III] lines as a contributor to cooling. On the other hand, the sulphur lines are less sensitive to temperature, therefore the reversal in the relation between their intensities and the average nebular abundance is expected to occur at a higher metallicity and the relation should remain single-valued for longer.

From the observational point of view they present two important advantages: first, the lines are easily detected both in high- and low-excitation ionized regions (Díaz et al. 1990) and secondly, they are less affected by reddening; moreover, they can be measured relative to nearby hydrogen recombination lines, H $\alpha$

**Table 1.** Oxygen and sulphur emission-line intensities.

Galaxy	Region	Ref.	[O II] 3727 + 3729	$\Delta$	[O III] 4959 + 5007	$\Delta$	[S II] 6716 + 6731	$\Delta$	[S III] 9069 + 9532	$\Delta$	c(H $\beta$ )
MWG	NGC 2467	1	0.49	–	0.41	–	–0.71	–	–0.13	–	0.60
–	ETACAR	1	0.19	–	0.48	–	–0.54	–	0.10	–	0.70
–	M17	1	0.05	–	0.65	–	–1.19	–	0.18	–	1.32
–	M16	1	0.21	–	0.28	–	–0.65	–	–0.14	–	1.12
–	M20	1	0.53	–	0.07	–	–0.38	–	0.07	–	0.66
–	NGC 3576	1	0.13	–	0.65	–	–0.87	–	0.44	–	0.76
–	ORION 1	1	0.01	–	0.59	–	–1.38	–	0.02	–	0.85
–	ORION 2	1	0.00	–	0.67	–	–1.32	–	0.25	–	0.63
–	S209	19	0.08	0.03	0.61	0.01	–0.82	0.06	–0.52	0.08	3.08
–	S283	19	0.60	0.05	–0.33	0.05	–0.11	0.05	–0.52	0.08	1.44
–	S98	19	0.57	0.05	–0.26	0.13	–0.31	0.06	–0.48	0.09	2.35
–	S127	19	0.40	0.05	0.22	0.03	–0.76	0.04	–0.23	0.07	2.37
–	S128	19	0.32	0.05	0.59	0.01	–0.72	0.05	–0.20	0.08	2.25
IC10	# 2	4	0.16	0.05	0.85	0.05	–0.70	0.06	0.02	0.06	1.48
SMC	N80	1	0.54	–	0.53	–	–0.85	–	–0.37	–	–1.00
–	N83	1	0.36	–	0.63	–	–0.52	–	–0.29	–	0.12
–	N13	1	0.49	–	0.72	–	–1.01	–	–0.13	–	–1.00
–	N32	1	0.70	–	–0.54	–	–0.46	–	–0.50	–	0.15
–	N81	1	0.11	–	0.85	–	–0.93	–	–0.14	–	0.04
–	N66	1	–0.02	–	0.84	–	–0.97	–	–0.42	–	0.17
NGC 295	1	21	0.44	0.04	0.45	0.09	–0.41	0.07	–0.32	0.15	0.50
–	2	21	0.56	0.03	0.52	0.09	–0.31	0.06	–0.42	0.16	0.57
–	3	21	0.52	0.04	0.61	0.10	–0.36	0.08	–0.21	0.18	0.60
–	6	21	0.24	0.04	0.72	0.08	–0.51	0.06	–0.07	0.16	0.43
–	7	21	0.59	0.05	0.23	0.12	–0.30	0.09	–0.35	0.16	0.54
–	8	21	0.40	0.04	0.31	0.10	–0.20	0.08	–0.14	0.14	0.39
–	9	21	0.29	0.09	0.77	0.14	–0.36	0.12	–0.14	0.18	0.40
M33	CC93	20	0.24	–	–0.80	–	–0.06	0.05	–0.27	0.03	0.20
–	IC142	20	0.36	0.01	0.01	0.01	–0.32	0.07	0.05	0.02	0.24
–	NGC 595	20	0.33	0.01	0.28	0.01	–0.60	0.04	–0.01	0.01	0.49
–	NGC 595	4	0.33	0.01	0.28	0.01	–0.51	0.05	0.01	0.05	0.49
–	MA 2	20	0.26	0.02	0.36	0.01	–0.71	0.02	0.01	0.02	0.10
–	NGC 604	20	0.33	0.01	0.46	0.01	–0.43	0.04	–0.06	0.01	0.36
–	NGC 604	4	0.33	0.02	0.46	0.01	–0.51	0.05	–0.17	0.05	0.36
–	NGC 588	20	0.17	0.02	0.80	0.01	–0.72	0.11	–0.03	0.02	0.15
–	NGC 588	4	0.17	0.02	0.80	0.01	–0.64	0.05	–0.01	0.07	0.15
–	IC131	4	0.32	0.01	0.72	0.01	–0.57	0.10	–0.06	0.08	0.10
NGC 753	1	12	0.26	0.15	0.35	0.10	–0.20	0.15	–0.92	0.40	0.72
–	4	12	–0.15	0.15	0.35	0.10	–0.13	0.15	–0.68	0.30	0.18
–	17	12	–0.04	0.15	–0.53	0.10	–0.28	0.15	–0.42	0.30	0.85
–	20	12	0.00	0.15	0.29	0.10	–0.41	0.15	–0.88	0.30	0.35
–	23	12	0.06	0.15	0.40	0.10	–0.09	0.15	–1.00	0.30	0.99
Mkn 600	–	4	0.22	0.04	0.94	0.04	–0.73	0.09	–0.57	0.17	0.66
LMC	N59A	1	0.26	–	0.86	–	–0.87	–	–0.07	–	0.19
–	N44B	1	0.20	–	1.03	–	–0.74	–	0.02	–	0.09
–	N55A	1	0.33	–	0.56	–	–0.96	–	–0.01	–	0.10
–	N113D	1	0.68	–	0.50	–	–0.67	–	0.08	–	–1.00
–	N127A	1	0.65	–	0.49	–	–0.73	–	0.06	–	–1.00
–	N159A	1	0.11	–	0.79	–	–1.01	–	–0.02	–	0.43
–	N214C	1	0.52	–	0.59	–	–0.37	–	–0.05	–	0.00
–	N4A	1	0.13	–	0.75	–	–0.90	–	–0.03	–	0.25
–	N79E	1	0.43	–	0.24	–	–0.53	–	–0.15	–	0.16
–	N191A	1	0.86	–	–	–	–0.43	–	0.00	–	–1.00
IIZw40	–	4	–0.26	0.02	1.006	0.004	–0.83	0.06	–0.34	0.07	1.23
IIZw40	–	2	–0.26	0.02	1.006	0.004	–0.98	0.03	–0.23	0.03	1.23
NGC 2366	NGC 2363	4	–0.24	0.02	0.97	0.01	–1.06	0.06	–0.450	0.14	0.25
NGC 2366	NGC 2363 A1	8	0.30	0.08	0.72	0.08	–0.52	0.08	–0.39	0.21	0.19
–	NGC 2363 A2	8	–0.36	0.01	1.00	0.01	–1.17	0.01	–0.50	0.02	0.20
–	NGC 2363 A3	8	–0.10	0.18	0.91	0.07	–0.83	0.08	–0.29	0.22	0.18
–	NGC 2363 A4	8	0.00	0.26	0.90	0.07	–0.60	0.11	–0.22	0.30	0.18
NGC 2403	VS35	5	0.39	0.06	0.26	0.04	–0.32	0.01	–0.10	0.03	1.06
–	VS24	5	0.38	0.04	0.24	0.04	–0.46	0.01	–0.04	0.04	–0.07
–	VS38	5	0.28	0.05	0.13	0.04	–0.52	0.01	–0.07	0.05	0.28
–	VS44	5	0.45	0.14	0.30	0.04	–0.41	0.01	–0.15	0.05	0.40
–	VS51	5	0.36	0.13	0.37	0.04	–0.47	0.01	–0.10	0.07	0.52
–	VS3	5	0.35	0.09	0.33	0.04	–0.49	0.01	–0.11	0.07	0.60
–	VS49	5	0.34	0.05	0.51	0.04	–0.39	0.01	–0.13	0.06	–0.10
NGC 2541	6	21	0.35	0.09	0.66	0.19	–0.50	0.19	–1.15	0.36	0.38
–	16	21	0.28	0.07	0.74	0.09	–0.55	0.07	–0.21	0.16	0.44
–	17	21	0.40	0.04	0.63	0.09	–0.47	0.09	–0.38	0.15	0.36

Table 1 – *continued*

Galaxy	Region	Ref.	[O II]	$\Delta$	[O III]	$\Delta$	[S II]	$\Delta$	[S III]	$\Delta$	c(H $\beta$ )
			3727 + 3729		4959 + 5007		6716 + 6731		9069 + 9532		
–	19	21	0.48	0.04	0.46	0.09	–0.21	0.07	–0.21	0.16	0.42
UGC4483	–	18	–0.08	0.03	0.61	0.02	–0.93	0.01	–0.54	0.07	0.10
NGC 2903	4	21	0.24	0.04	–0.01	0.09	–0.30	0.06	–0.21	0.14	0.28
–	5	21	0.00	0.05	–0.51	0.12	–0.26	0.07	–0.18	0.17	0.76
–	6	21	–0.36	0.08	–0.87	0.16	–0.41	0.07	–0.62	0.15	0.50
–	18	21	–0.20	0.08	–0.92	0.24	–0.27	0.12	–0.56	0.24	0.95
NGC 2903	R1	15	–0.31	0.02	–0.76	0.03	–0.28	0.02	–0.56	0.10	0.82
–	R2	15	–0.37	0.03	–0.97	0.05	–0.28	0.02	–0.76	0.08	0.74
–	R3	15	–0.17	0.04	–0.41	0.04	–0.14	0.02	–0.16	0.13	0.46
–	R4	15	–0.24	0.04	–0.76	0.03	–0.23	0.02	–0.69	0.07	0.92
–	R6	15	–0.46	0.04	–1.03	0.06	–0.28	0.02	–0.69	0.07	0.79
–	R7	15	–0.41	0.03	–0.83	0.04	–0.24	0.01	–0.56	0.10	0.99
–	R8	15	–0.32	0.02	–0.76	0.03	–0.25	0.02	–0.69	0.07	0.96
IZw18	–	4	–0.59	0.06	0.46	0.01	–1.18	0.09	–0.85	0.18	0.04
IZw18	SE	17	–0.33	0.03	0.39	0.09	–1.15	0.34	–1.02	0.16	0.20
–	NW	17	–0.59	0.02	0.44	0.09	–1.45	0.34	–1.09	0.16	0.10
NGC 3310	Nuc	14	0.61	0.01	0.25	0.02	0.13	0.01	–0.01	0.01	0.63
–	A	14	0.41	0.01	0.48	0.01	–0.31	0.01	–0.37	0.01	0.29
–	B	14	0.49	0.01	0.38	0.01	–0.16	0.01	–0.22	0.01	0.20
–	C	14	0.50	0.01	0.51	0.01	–0.25	0.01	–0.09	0.01	0.34
–	E	14	0.50	0.01	0.44	0.01	–0.21	0.02	–0.12	0.01	0.26
–	L	14	0.67	0.01	0.36	0.02	–0.07	0.02	–0.17	0.02	0.53
–	M	14	0.40	0.01	0.53	0.03	–0.22	0.12	–0.11	0.10	0.14
NGC 3351	R1	15	–0.37	0.03	–1.03	0.06	–0.35	0.02	–0.38	0.03	0.81
–	R2	15	–0.52	0.04	–0.92	0.05	–0.33	0.02	–0.56	0.10	0.24
–	R3	15	–0.52	0.03	–1.10	0.07	–0.37	0.03	–0.56	0.06	0.64
–	R4	15	–0.60	0.05	–1.18	0.08	–0.35	0.04	–0.35	0.06	0.24
–	R5	15	–0.26	0.03	–0.53	0.04	–0.21	0.04	–0.42	0.04	0.35
–	R7	15	–0.60	0.11	–1.10	0.07	–0.41	0.07	–0.76	0.15	0.28
–	R8	15	–0.60	0.06	–1.03	0.06	–0.37	0.05	–0.86	0.18	0.36
Mkn 36	–	4	0.10	0.04	0.85	0.04	–0.60	0.06	–0.54	0.17	0.12
NGC 3504	R2	15	–0.15	0.02	–0.80	0.03	–0.18	0.03	–0.29	0.03	0.28
–	R3	15	–0.12	0.02	–0.62	0.02	–0.19	0.02	–0.35	0.03	0.59
–	R4	15	–0.15	0.04	–0.55	0.02	–0.12	0.03	–0.38	0.03	0.49
NGC 3521	5	21	0.07	0.09	–0.96	0.16	–0.37	0.13	–0.69	0.30	0.98
–	7	21	0.41	0.05	–0.46	0.20	–0.20	0.12	0.08	0.23	1.24
–	8	21	0.61	0.05	0.62	0.12	–0.35	0.12	0.00	0.20	0.93
–	9	21	0.54	0.07	0.17	0.16	–0.23	0.14	0.24	0.22	0.75
NGC 3621	1	21	0.32	0.03	–0.02	0.08	–0.23	0.05	–0.51	0.16	0.31
–	2	21	0.22	0.06	–0.10	0.11	–0.27	0.08	–0.69	0.18	0.13
–	3	21	0.50	0.04	0.24	0.10	–0.26	0.07	–1.16	0.18	0.84
NGC 4253	A	6	0.20	0.07	0.71	0.03	–0.08	0.04	–0.03	0.06	0.51
–	B	6	0.43	0.05	0.65	0.03	–0.10	0.03	–0.05	0.06	0.45
NGC 4254	142	10	–0.49	0.10	–0.97	0.14	–0.55	0.03	–0.46	0.04	0.77
–	78	10	–0.06	0.06	–1.27	0.30	–0.40	0.03	–0.51	0.05	0.82
–	173	10	–0.20	0.05	–1.03	0.10	–0.46	0.02	–0.42	0.04	0.38
–	185	10	0.16	0.09	–0.32	0.05	–0.32	0.02	–0.62	0.06	1.20
–	184	10	0.28	0.05	0.06	0.02	–0.19	0.03	–0.42	0.04	0.32
–	84	10	0.49	0.05	–0.19	0.05	–0.19	0.04	–0.12	0.06	0.58
–	22	10	0.51	0.03	0.03	0.02	–0.22	0.02	–0.12	0.03	0.59
–	12	10	0.52	0.06	–0.25	0.07	–0.12	0.05	–0.08	0.07	0.29
NGC 4303	95	11	0.09	0.12	–0.76	0.19	–0.29	0.11	–0.29	0.22	0.32
–	115	11	0.19	0.03	–0.80	0.15	–0.28	0.06	–0.69	0.18	0.78
–	155	11	0.11	0.04	–0.70	0.05	–0.32	0.05	–0.46	0.08	0.43
–	51	11	0.45	0.12	–0.51	0.18	–0.28	0.09	–0.76	0.20	0.74
–	76	11	0.40	0.08	–0.22	0.06	–0.29	0.09	–0.51	0.16	0.52
–	53	11	0.26	0.12	–0.48	0.25	–0.12	0.22	–0.69	0.18	0.38
–	103	11	0.24	0.13	–0.60	0.13	–0.26	0.12	–0.51	0.19	0.55
–	124	11	0.50	0.17	–0.48	0.17	–0.12	0.11	–0.42	0.13	0.48
–	148	11	0.48	0.08	–0.12	0.08	–0.19	0.08	–0.56	0.21	0.20
–	278	11	0.46	0.05	0.42	0.05	–0.21	0.08	–0.69	0.15	0.13
–	234	11	0.65	0.06	0.55	0.06	0.02	0.07	–0.12	0.21	0.00
NGC 4528	4	21	0.29	0.03	0.16	0.07	–0.62	0.05	0.12	0.18	0.37
NGC 4559	1	21	0.43	0.04	0.02	0.11	–0.13	0.09	–0.14	0.15	0.46
–	3	21	0.43	0.04	0.52	0.10	–0.32	0.07	–0.10	0.14	0.17
–	4	21	0.39	0.04	0.60	0.09	–0.58	0.08	–0.86	0.18	0.17
–	17	21	0.41	0.04	0.38	0.09	–0.28	0.07	0.12	0.16	0.49
–	18	21	0.48	0.03	0.35	0.07	–0.43	0.06	0.07	0.15	0.31
–	19	21	0.47	0.03	0.05	0.11	–0.28	0.08	0.01	0.17	0.45
–	20	21	0.43	0.04	0.00	0.10	–0.35	0.08	0.04	0.16	0.53
NGC 4861	–	4	0.11	0.04	0.92	0.04	–0.75	0.06	–0.32	0.07	0.09

Table 1 – continued

Galaxy	Region	Ref.	[O II]	$\Delta$	[O III]	$\Delta$	[S II]	$\Delta$	[S III]	$\Delta$	c(H $\beta$ )
			3727 + 3729		4959 + 5007		6716 + 6731		9069 + 9532		
M51	CCM72	3	-0.21	0.02	-1.18	0.15	-0.43	0.04	-0.29	0.06	0.31
-	CCM24	3	0.01	0.01	-0.65	0.20	-0.38	0.03	-0.48	0.15	0.60
-	CCM10	3	0.21	0.01	-0.58	0.04	-0.40	0.06	-0.48	0.04	0.30
M101	H602	13	-0.59	0.03	-0.96	0.10	-0.47	0.04	-0.68	0.12	0.39
-	H493	13	0.05	0.11	-0.89	0.09	-0.32	0.03	-0.37	0.09	0.50
-	H507	13	-0.19	0.03	-1.00	0.04	-0.31	0.02	-0.41	0.09	0.46
-	H972	13	0.14	0.02	-0.40	0.03	-0.47	0.03	-0.14	0.08	0.30
-	H942	13	0.17	0.04	-0.41	0.07	-0.25	0.04	-0.30	0.10	0.52
-	H974	13	0.21	0.03	-0.47	0.10	-0.34	0.05	-0.66	0.16	0.33
-	H959	13	0.48	0.09	-0.42	0.05	-0.21	0.02	-0.28	0.09	0.52
-	H1013	13	0.26	0.02	0.12	0.02	-0.64	0.02	0.06	0.08	0.30
-	H399	13	0.19	0.05	-0.18	0.03	-0.46	0.02	-0.03	0.08	0.32
-	H1044	13	0.28	0.03	-0.12	0.03	-0.44	0.02	-0.06	0.08	0.28
-	H953	13	0.27	0.06	-0.25	0.04	-0.37	0.02	-0.33	0.08	0.24
-	H949	13	0.23	0.05	-0.43	0.03	-0.30	0.02	-0.17	0.08	0.39
-	H1052	13	0.32	0.04	0.50	0.02	-0.64	0.02	0.12	0.08	0.29
-	H203	13	0.36	0.02	-0.27	0.02	-0.26	0.02	-0.17	0.08	0.22
-	H1086	13	0.43	0.05	0.37	0.03	-0.46	0.01	-0.09	0.08	0.32
-	H875	13	0.53	0.05	0.09	0.03	-0.29	0.03	-0.21	0.08	0.43
-	H1098	13	0.49	0.04	0.18	0.02	-0.40	0.02	0.04	0.08	0.74
-	H237	13	0.11	0.02	0.19	0.02	-0.49	0.03	-0.25	0.08	0.20
-	H1026	13	0.37	0.02	0.57	0.02	-0.57	0.02	-0.07	0.08	0.11
-	H178	13	0.65	0.04	0.26	0.04	-0.43	0.02	-0.14	0.08	0.59
-	H1159	13	0.40	0.03	0.61	0.02	-0.64	0.02	-0.04	0.08	0.25
-	H1170	13	0.38	0.02	0.63	0.02	-0.54	0.03	-0.03	0.08	0.39
-	H1176	13	0.32	0.02	0.62	0.02	-0.70	0.02	0.00	0.08	0.39
-	H140	13	0.45	0.02	0.20	0.02	-0.11	0.02	-0.19	0.08	0.13
-	H1191	13	0.34	0.03	0.67	0.03	-0.60	0.03	-0.13	0.09	0.35
-	H119	13	0.49	0.09	0.35	0.03	-0.12	0.03	-0.52	0.10	0.33
-	H132	13	0.48	0.02	0.46	0.02	-0.34	0.02	-0.48	0.08	0.28
-	H143	13	0.45	0.02	0.54	0.02	-0.36	0.02	-0.08	0.08	0.39
-	H149	13	0.45	0.02	-0.39	0.02	-0.42	0.01	-0.06	0.08	0.45
-	H128	13	0.26	0.02	0.72	0.02	-0.70	0.02	-0.01	0.08	0.27
-	H67	13	0.37	0.02	0.68	0.02	-0.68	0.04	-0.13	0.08	0.07
-	H1216	13	0.29	0.03	0.79	0.02	-0.85	0.03	-0.07	0.08	0.17
-	H681	13	0.39	0.03	0.61	0.03	-0.57	0.05	-0.44	0.10	0.22
-	NGC 5471	16	0.06	0.04	0.89	0.04	-0.61	0.05	-0.20	0.05	0.18
-	NGC 5471	4	0.12	0.01	0.96	0.01	-0.70	0.05	-0.32	0.07	0.15
-	NGC 5471A	13	0.11	0.03	0.97	0.02	-0.82	0.03	-0.30	0.08	0.22
-	NGC 5471A	2	0.17	0.03	0.81	0.02	-0.73	0.03	-0.35	0.03	0.25
-	NGC 5471B	13	0.45	0.03	0.75	0.02	-0.27	0.02	-0.30	0.08	0.23
-	NGC 5471C	13	0.36	0.03	0.80	0.02	-0.60	0.02	-0.20	0.08	0.19
-	NGC 5471D	13	0.18	0.03	0.91	0.02	-0.80	0.03	-0.13	0.08	0.09
-	NGC 5471E	13	0.10	0.03	0.91	0.02	-0.92	0.04	-0.14	0.08	0.24
-	S5	13	0.28	0.02	-0.48	0.03	-0.29	0.02	-0.10	0.08	0.30
-	S5	16	0.26	0.05	-0.49	0.06	-0.19	0.05	0.07	0.10	0.22
-	S5	2	0.32	0.04	-0.47	0.03	-0.17	0.05	0.30	0.07	0.50
-	NGC 5455	13	0.32	0.02	0.68	0.02	-0.52	0.01	-0.08	0.08	0.12
-	NGC 5455	16	0.41	0.04	0.68	0.04	-0.43	0.05	0.00	0.05	0.15
-	NGC 5461	13	0.22	0.02	0.64	0.02	-0.68	0.02	0.08	0.08	0.36
-	NGC 5461A	2	0.27	0.02	0.64	0.02	-0.47	0.02	0.00	0.01	0.60
NGC 5953	A	7	-0.10	0.10	-0.52	0.04	-0.20	0.02	-0.46	0.04	0.00
-	B	7	-0.05	0.09	-0.44	0.06	-0.19	0.03	-0.49	0.05	0.00
-	C	7	0.20	0.07	0.36	0.02	-0.02	0.02	-0.44	0.03	0.00
IZw123	-	4	0.10	0.04	0.96	0.04	-0.64	0.06	-0.45	0.15	0.38
NGC 7714	A	9	0.39	0.01	0.25	0.01	-0.13	0.01	-0.21	0.02	0.33
-	N110	9	0.26	0.02	0.27	0.01	-0.24	0.03	-0.02	0.05	0.30
-	B	9	0.38	0.01	0.68	0.01	-0.28	0.02	-0.31	0.02	0.37
-	C	9	0.45	0.04	0.54	0.01	-0.24	0.05	-0.38	0.09	0.44
-	N216	9	0.24	0.02	0.31	0.01	-0.23	0.03	0.03	0.05	0.30

References to the table.

1: Dennefeld & Stasińska (1983); 2: Díaz et al. (1990); 3: Díaz et al. (1991); 4: Garnett (1989); 5: Garnett et al. (1997); 6: González-Delgado & Pérez (1996a); 7: González-Delgado & Pérez (1996b); 8: González-Delgado et al. (1994); 9: González-Delgado et al. (1995); 10: Henry et al. (1992); 11: Henry, Pagel & Chincarini (1994); 12: Henry et al. (1996); 13: Kennicutt & Garnett (1996); 14: Pastoriza et al. (1993); 15: Pérez-Olea (1996); 16: Shields & Searle (1978); 17: Skillman & Kennicutt (1993); 18: Skillman et al. (1993); 19: Vílchez & Esteban (1996); 20: Vílchez et al. (1988); 21: Zaritsky, Kennicutt & Huchra (1994).

in the case of the [S II] lines and Paschen lines in the case of the [S III] lines, which also minimizes any flux calibration uncertainties. These lines are accessible spectroscopically with CCD detectors up to a redshift of about 0.1.

## 2 OBSERVATIONAL DATA

In the last decade there has been a considerable increase in the amount of near-infrared [S III] emission-line data. We have compiled from the literature all the ‘H II region like’ objects for which measurements of these lines, together with optical emission lines, exist. The sample includes H II regions in our own Galaxy, H II regions in spirals and irregular galaxies and H II galaxies. The data are presented in Table 1, where the logarithmic intensities of the emission lines with respect to H $\beta$  are given, together with their corresponding observational errors when quoted in the original reference. These references are numbered in column 3 and listed at the bottom of the table. The observed intensities were corrected for reddening according to the derived logarithmic extinction at H $\beta$  listed in the last column of the table and a standard reddening law. The sample comprises a total of 196 objects.

Only 65 of these objects have electron temperatures derived directly. Table 2 lists for these objects their electron temperature, in units of  $10^4$  K, and their derived oxygen abundance expressed as  $12 + \log O/H$ . The electron temperature has been derived from the measured intensity of the [O III]  $\lambda 4363$  line, except for the objects marked with an asterisk, for which a measurement of the [O II]  $\lambda 7327$  line has been used. The total oxygen abundance has been calculated as  $\log O/H = \log(O^+/H^+ + O^{++}/H^+)$ . The errors in the abundances have been derived from those quoted for the emission lines whenever possible. For the H II regions in the Magellanic Clouds (Dennefeld & Stasińska 1983) we have adopted an abundance error of  $\pm 0.10$ .

The oxygen abundance ranges from 2 per cent solar for IZw18 to 70 per cent solar for region VS24 in NGC 2403.

We have included in the table data for three regions of metallicity close to solar, for which detailed modelling has been done: CC93 in M33 (Vílchez et al. 1988), S5 in M101 (Shields & Searle 1978; Díaz et al. 1990) and the nucleus of NGC 3310 (Pastoriza et al. 1993).

## 3 RESULTS AND DISCUSSION

From the line intensities of the sulphur lines presented in Table 1, we have calculated the *sulphur abundance parameter*  $S_{23}$ , defined as

$$S_{23} = \frac{[\text{S II}]\lambda\lambda 6717, 6731 + [\text{S III}]\lambda\lambda 9069, 9532}{\text{H}\beta}.$$

This parameter is analogous to the  $R_{23}$  parameter defined for the optical oxygen lines, and hereafter we will refer to the oxygen and sulphur abundance parameters as  $O_{23}$  and  $S_{23}$  respectively. Both parameters are listed in Table 2.

The relation between  $O_{23}$  and the oxygen abundance for the objects in Table 2 can be seen in the upper panel of Fig. 1 (solid dots) together with similar data for H II galaxies compiled by Díaz (1998) (open circles). The figure illustrates the problems mentioned in the Introduction, the most important one being the two-valued nature of the relation which makes an accurate metallicity calibration virtually impossible, more so for objects

with  $\log O_{23} \geq 0.8$ . Also notice the position of the nucleus of NGC 3310, which is probably the result of its higher than usual density ( $n_{\text{H}} = 8000 \text{ cm}^{-3}$ ; Pastoriza et al. 1993).

In contrast, and as expected, the relation between  $S_{23}$  and oxygen abundance for the objects of Table 2, shown in the lower panel of the figure, remains single-valued up to a metallicity close to solar. In both figures the data corresponding to different observations of IZw18, NGC 5471 in M101, and S5 in M101 have been joined together to show the importance of internal errors. The solar metallicity regions have also been labelled. Also, compared with the case of  $O_{23}$ , the scatter in the relation between  $S_{23}$  and oxygen abundance is somewhat reduced.

The dependence of  $O_{23}$  on the degree of ionization of the nebula is partially responsible for the large scatter found in the  $O_{23}$  versus metallicity relation. Fig. 2 (upper panel) shows the relation between  $\log O_{23}$  and  $\log([O \text{ II}]/[O \text{ III}])$ , which can be taken as a good ionization parameter indicator for ionizing temperatures larger than about 35 000 K (see Díaz, 1998), for the objects in Table 1. A positive correlation between ionization parameter and  $O_{23}$  is evident for objects with  $O_{23}$  between 0.2 and 1 (higher excitation objects are at the left in the plot). In contrast, no relation between  $\log S_{23}$  and  $\log([O \text{ II}]/[O \text{ III}])$  is readily apparent in the lower panel of the figure. The peculiar position of IZw18 in the plots is the result of its very low metallicity.

Based on the above considerations, we have attempted a calibration of oxygen abundance through the sulphur abundance parameter  $S_{23}$ , using the data of Table 2 with the exclusion of the three objects for which no direct determinations of the electron temperature exist: S5 in M101, CC93 in M33 and the nucleus of NGC 3310. A linear fit to the data, taking into account the observational errors, gives

$$12 + \log(O/H) = 1.53 \log S_{23} + 8.27,$$

with a correlation coefficient of 0.88 and a value of  $\sigma = 0.15$ .

The data points corresponding to IZw18 deviate slightly from linearity. This is caused by the high excitation of this object, which increases the fraction of  $S^{++}$  converted to  $S^{3+}$ , thus decreasing  $S_{23}$ . A quadratical fit

$$12 + \log(O/H) = 0.24(\log S_{23})^2 + 1.42 \log S_{23} + 8.25$$

provides a better fit to these extremely low metallicity data. The two fits are shown in the upper panel of Fig. 3 by solid and dashed lines respectively. The corresponding residuals are shown in the lower panel as a function of the oxygen abundance. Solid dots correspond to the linear fit, while open circles correspond to the quadratic one.

Fig. 4 shows the relation between  $S_{23}$  and  $O_{23}$ . The largest value of  $S_{23}$  corresponds to one of the observations of region S5 in M101 ( $S_{23} = 0.48$ ), and the solar metallicity objects have  $S_{23}$  between 0.28 and 0.48. On the other hand, the object with the lowest metallicity known, IZw18, has a value of  $\log O_{23} = 0.47$ . These two facts taken together imply that objects with  $\log O_{23} \leq 0.47$  and  $-0.5 < \log S_{23} \leq 0.28$  will necessarily have oversolar abundances. 48 out of the 196 objects listed in Table 1 fall into this class, which therefore constitutes about a quarter of the total sample. Most of them are circumnuclear star-forming regions, H II regions in inner galactic discs and H II regions in Virgo cluster galaxies.

For  $\log O_{23} > 0.45$  it can be seen that for the lowest metallicity objects there is a positive correlation between  $O_{23}$  and  $S_{23}$ ; NGC 5471, with  $\log O_{23} \approx 1.00$  and  $\log S_{23} \approx 0.10$ , would lie at the

**Table 2.** Oxygen abundance and abundance parameters for the sample objects.

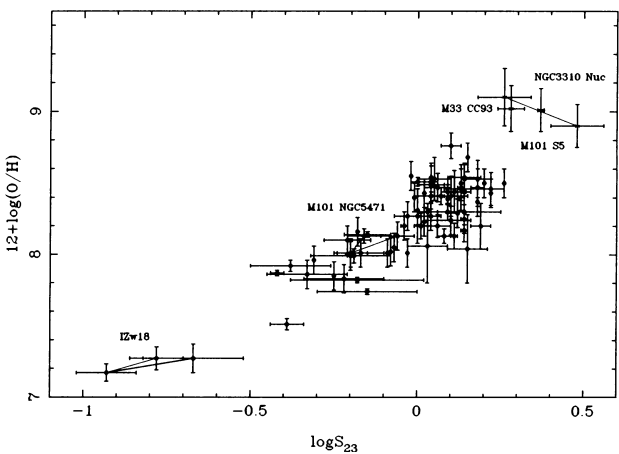
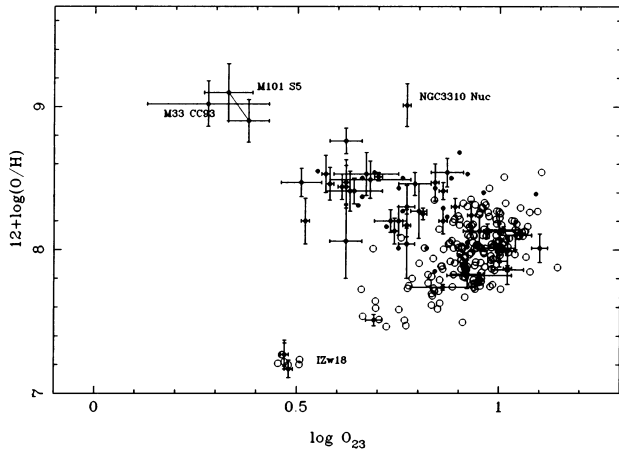
Galaxy	Region	Ref	$\log O_{23}$	$\log S_{23}$	$12 + \log(O/H)$	$t_e(10^4 \text{ K})$
MWG	N2467	1	$0.75 \pm 0.04$	$-0.03$	$8.01 \pm 0.10$	1.18
–	ETACAR	1	$0.66 \pm 0.04$	0.18	$8.37 \pm 0.10$	0.89
–	M17	1	$0.75 \pm 0.04$	0.22	$8.43 \pm 0.10$	0.88
–	M16	1	$0.55 \pm 0.04$	$-0.02$	$8.55 \pm 0.10$	1.81
–	M20	1	$0.66 \pm 0.04$	0.20	$8.50 \pm 0.10$	2.73
–	NGC 3576	1	$0.76 \pm 0.04$	0.46	$8.42 \pm 0.10$	0.91
–	Orion1	1	$0.69 \pm 0.04$	0.04	$8.54 \pm 0.10$	0.84
–	Orion2	1	$0.76 \pm 0.04$	0.26	$8.50 \pm 0.10$	0.87
–	S127*	19	$0.62 \pm 0.04$	$-0.12 \pm 0.06$	$8.06 \pm 0.26$	0.80
–	S128*	19	$0.78 \pm 0.02$	$-0.09 \pm 0.06$	$8.04 \pm 0.24$	0.90
IC10	# 2	4	$0.93 \pm 0.01$	$0.09 \pm 0.06$	$8.26 \pm 0.10$	1.08
SMC	N80	1	$0.84 \pm 0.04$	$-0.25$	$7.85 \pm 0.10$	1.39
–	N83	1	$0.82 \pm 0.04$	$-0.09$	$8.01 \pm 0.10$	1.21
–	N13	1	$0.92 \pm 0.04$	$-0.08$	$8.02 \pm 0.10$	1.30
–	N32	1	$0.72 \pm 0.04$	$-0.18$	$8.16 \pm 0.10$	2.13
–	N81	1	$0.92 \pm 0.04$	$-0.07$	$8.05 \pm 0.10$	1.26
–	N66	1	$0.90 \pm 0.04$	$-0.31$	$7.96 \pm 0.10$	1.31
M33	N604	4	$0.70 \pm 0.01$	$0.04 \pm 0.02$	$8.51 \pm 0.03$	0.82
–	N604	20	$0.70 \pm 0.01$	$0.00 \pm 0.02$	$8.51 \pm 0.03$	0.77
–	N595	4	$0.61 \pm 0.01$	$0.09 \pm 0.02$	$8.44 \pm 0.09$	0.90
–	N595	20	$0.61 \pm 0.01$	$0.04 \pm 0.02$	$8.44 \pm 0.09$	0.80
–	N588	4	$0.89 \pm 0.01$	$0.09 \pm 0.03$	$8.33 \pm 0.06$	0.94
–	N588	20	$0.89 \pm 0.01$	$0.03 \pm 0.03$	$8.33 \pm 0.06$	1.01
–	MA2	20	$0.61 \pm 0.01$	$0.09 \pm 0.02$	$8.44 \pm 0.15$	0.80
–	IC142	20	$0.52 \pm 0.01$	$0.19 \pm 0.03$	$8.69 \pm 0.16$	0.69
–	IC131	4	$0.87 \pm 0.01$	$0.06 \pm 0.08$	$8.41 \pm 0.06$	0.95
–	CC93	20	$0.28 \pm 0.15$	$0.28 \pm 0.04$	$9.02 \pm 0.16$	0.55
Mkn600	–	4	$1.02 \pm 0.04$	$-0.34 \pm 0.12$	$7.86 \pm 0.10$	1.64
LMC	N59A	1	$0.96 \pm 0.04$	$-0.01$	$8.40 \pm 0.10$	1.01
–	N44B	1	$1.09 \pm 0.04$	0.09	$8.39 \pm 0.10$	1.11
–	N55A	1	$0.76 \pm 0.04$	0.04	$8.27 \pm 0.10$	0.98
–	N113D	1	$0.90 \pm 0.04$	0.15	$8.68 \pm 0.10$	0.87
–	N127A	1	$0.88 \pm 0.04$	0.13	$8.50 \pm 0.10$	0.95
–	N159A	1	$0.87 \pm 0.04$	0.02	$8.23 \pm 0.10$	1.07
–	N214C	1	$0.86 \pm 0.04$	0.12	$8.29 \pm 0.10$	1.04
–	N4A	1	$0.84 \pm 0.04$	0.02	$8.43 \pm 0.10$	0.93
–	N79E	1	$0.65 \pm 0.04$	0.00	$8.31 \pm 0.10$	0.92
–	N191A	1	$0.92 \pm 0.04$	0.14	$8.53 \pm 0.10$	1.09
IIZw40	–	4	$1.04 \pm 0.04$	$-0.22 \pm 0.07$	$8.10 \pm 0.10$	1.33
IIZw40	–	2	$1.01 \pm 0.04$	$-0.15 \pm 0.07$	$8.14 \pm 0.02$	1.28
N2366	N2363	4	$1.00 \pm 0.02$	$-0.39 \pm 0.12$	$7.92 \pm 0.04$	1.48
–	N2363 A1	8	$0.86 \pm 0.08$	$-0.15 \pm 0.15$	$7.74 \pm 0.02$	1.62
–	N2363 A2	8	$1.02 \pm 0.01$	$-0.42 \pm 0.02$	$7.87 \pm 0.02$	1.61
–	N2363 A3	8	$0.95 \pm 0.08$	$-0.18 \pm 0.20$	$7.82 \pm 0.02$	1.59
N2403	VS35	5	$0.63 \pm 0.05$	$0.10 \pm 0.02$	$8.41 \pm 0.14$	0.84
–	VS24	5	$0.62 \pm 0.04$	$0.10 \pm 0.03$	$8.76 \pm 0.09$	0.68
–	VS38	5	$0.51 \pm 0.05$	$0.06 \pm 0.04$	$8.47 \pm 0.10$	0.76
–	VS44	5	$0.68 \pm 0.10$	$0.04 \pm 0.04$	$8.49 \pm 0.13$	0.87
–	VS51	5	$0.67 \pm 0.08$	$0.05 \pm 0.05$	$8.53 \pm 0.15$	0.80
–	VS3	5	$0.64 \pm 0.07$	$0.04 \pm 0.05$	$8.41 \pm 0.09$	0.87
–	VS49	5	$0.73 \pm 0.04$	$0.06 \pm 0.04$	$8.20 \pm 0.08$	1.05
UGC4483	–	18	$0.69 \pm 0.02$	$-0.39 \pm 0.05$	$7.51 \pm 0.04$	1.66
IIZw18	–	4	$0.47 \pm 0.01$	$-0.67 \pm 0.15$	$7.27 \pm 0.10$	1.80
IIZw18	SE	17	$0.47 \pm 0.01$	$-0.78 \pm 0.08$	$7.27 \pm 0.08$	1.72
–	NW	17	$0.48 \pm 0.02$	$-0.93 \pm 0.09$	$7.17 \pm 0.06$	1.96
N3310	Nuc	14	$0.77 \pm 0.01$	$0.37 \pm 0.01$	$9.01 \pm 0.15$	0.62
–	A	14	$0.75 \pm 0.01$	$-0.04 \pm 0.01$	$8.20 \pm 0.10$	1.04
–	B	14	$0.74 \pm 0.01$	$0.11 \pm 0.01$	$8.13 \pm 0.09$	1.21
–	C	14	$0.81 \pm 0.01$	$0.14 \pm 0.01$	$8.25 \pm 0.04$	0.95
–	E	14	$0.77 \pm 0.01$	$0.14 \pm 0.01$	$8.17 \pm 0.08$	0.98
–	L	14	$0.84 \pm 0.01$	$0.18 \pm 0.02$	$8.47 \pm 0.13$	0.70
–	M	14	$0.77 \pm 0.02$	$0.14 \pm 0.11$	$8.30 \pm 0.15$	0.97
Mkn36	–	4	$0.92 \pm 0.04$	$-0.27 \pm 0.12$	$7.86 \pm 0.10$	1.50
N4861	–	4	$1.10 \pm 0.02$	$-0.18 \pm 0.07$	$8.26 \pm 0.10$	1.21
M101	N5455	16	$0.87 \pm 0.04$	$0.14 \pm 0.05$	$8.54 \pm 0.10$	0.89
–	N5471	16	$0.95 \pm 0.04$	$-0.06 \pm 0.05$	$8.13 \pm 0.10$	1.19
–	N5471	2	$1.00 \pm 0.04$	$-0.20 \pm 0.05$	$8.01 \pm 0.10$	1.28
–	N5471	4	$1.00 \pm 0.04$	$-0.16 \pm 0.05$	$8.13 \pm 0.05$	1.30
–	N5461	2	$0.79 \pm 0.04$	$0.13 \pm 0.05$	$8.46 \pm 0.08$	0.90
–	S5	2	$0.38 \pm 0.05$	$0.48 \pm 0.08$	$8.90 \pm 0.15$	0.65
–	S5	16	$0.33 \pm 0.06$	$0.26 \pm 0.08$	$9.10 \pm 0.20$	0.58

**Table 2** – *continued*

Galaxy	Region	Ref	$\log O_{23}$	$\log S_{23}$	$12 + \log(O/H)$	$t_e(10^4 \text{ K})$
IZw123	–	4	$1.02 \pm 0.02$	$-0.23 \pm 0.12$	$8.01 \pm 0.10$	1.41
N7714	A	9	$0.62 \pm 0.01$	$0.13 \pm 0.01$	$8.47 \pm 0.16$	1.26
–	B	9	$0.86 \pm 0.01$	$0.01 \pm 0.02$	$8.20 \pm 0.09$	1.11
–	C	9	$0.80 \pm 0.02$	$0.00 \pm 0.07$	$8.27 \pm 0.19$	1.02
–	N110	9	$0.57 \pm 0.01$	$0.18 \pm 0.04$	$8.53 \pm 0.13$	1.10
–	N216	9	$0.58 \pm 0.01$	$0.22 \pm 0.04$	$8.46 \pm 0.12$	1.01

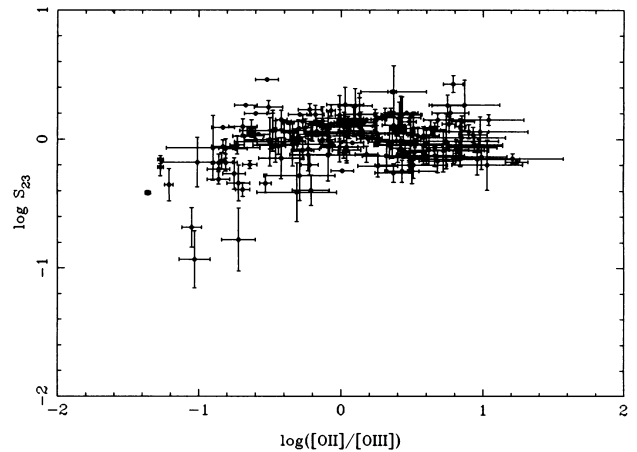
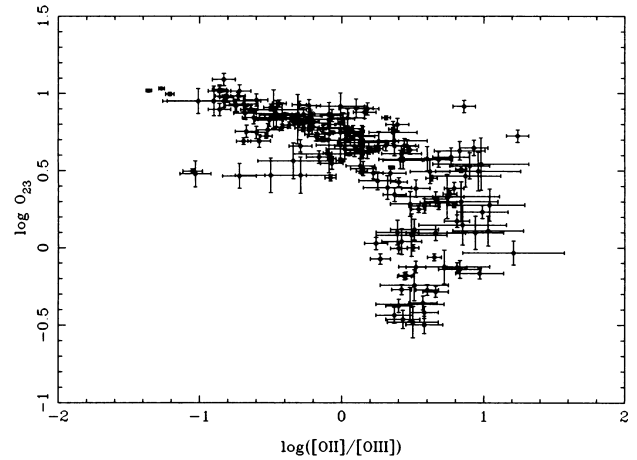
*References to the table.*

1: Dennefeld & Stasińska (1983); 2: Díaz et al. (1990); 3: Díaz et al. (1991); 4: Garnett (1989); 5: Garnett et al. (1997); 6: González-Delgado & Pérez (1996a); 7: González-Delgado & Pérez (1996b); 8: González-Delgado et al. (1994); 9: González-Delgado et al. (1995); 10: Henry et al. (1992); 11: Henry et al. (1994); 12: Henry et al. (1996); 13: Kennicutt & Garnett (1996); 14: Pastoriza et al. (1993); 15: Pérez-Olea (1996); 16: Shields & Searle (1978); 17: Skillman & Kennicutt (1993); 18: Skillman et al. (1993); 19: Vílchez & Esteban (1996); 20: Vílchez et al. (1988); 21: Zaritsky, Kennicutt & Huchra (1994).



**Figure 1.** Oxygen abundance parameter (upper panel) and sulphur abundance parameter (lower panel) versus oxygen abundance for the objects in Table 2 and H II galaxies in Díaz (1998).

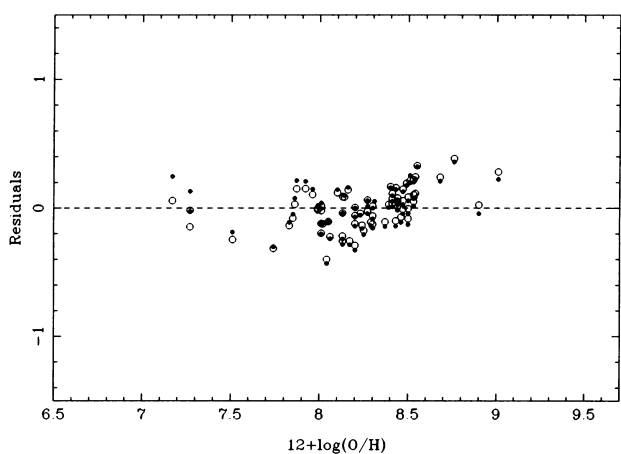
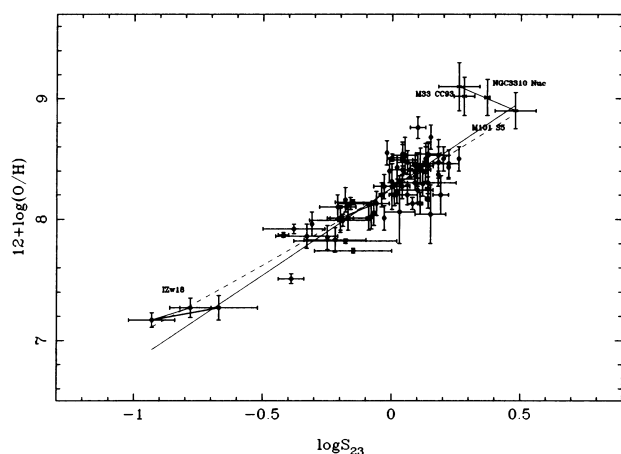
end of this correlation. Then, there is a trend of increasing  $S_{23}$  with decreasing  $O_{23}$  which corresponds to the ‘upper metallicity branch’ of the  $O_{23}$  abundance calibration. For values of  $\log O_{23}$  between 0.45 and 0.00, the relation between the two abundance parameters is rather flat. Finally, for values of  $\log O_{23} < 0.0$  a trend of decreasing  $S_{23}$  with decreasing  $O_{23}$  is apparent, indicating



**Figure 2.** Relation between  $\log O_{23}$  (upper panel) and  $\log S_{23}$  (lower panel) with  $\log([OII]/[OIII])$  taken as ionization parameter indicator, for the objects in Table 1.

that, for the metallicities involved, the expected reversal of the  $S_{23}$  versus metallicity relation has already taken place.

The behaviour of the  $O_{23}$  and  $S_{23}$  parameters is related to the different energies involved in the two sets of transitions and therefore a combination of both should, in principle, be a better indicator of metallicity than either of them alone. Fig. 5 shows a plot of  $\log(S_{23}/O_{23})$  for the H II regions in M101 (Kennicutt &

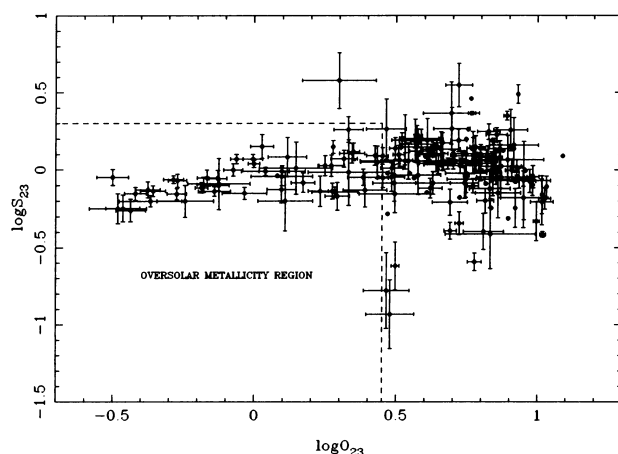


**Figure 3.** Empirical calibration of oxygen abundance through the sulphur abundance parameter  $S_{23}$ . The residuals of the fits are shown in the lower panel of the figure (see text for details).

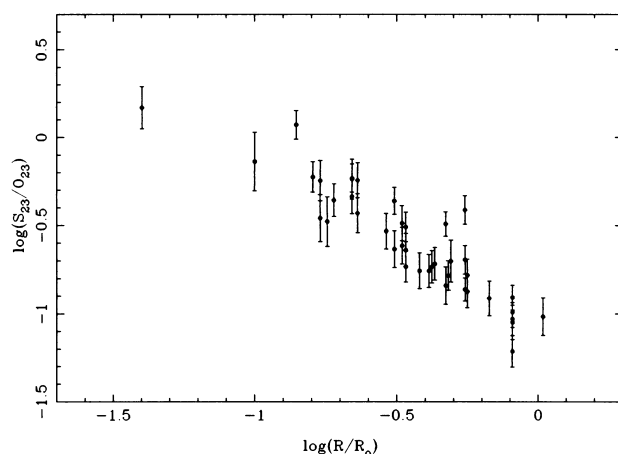
Garnett 1996). A single-line logarithmic gradient is found. This might actually constitute a purely observational way to quantify galactic disc abundance gradients without the need to rely on theoretical photoionization models.

#### 4 CONCLUSIONS

We have performed a new empirical calibration of nebular abundances using the sulphur abundance parameter  $S_{23}$ . This calibration is an alternative to the commonly used one based on the strong optical oxygen lines and presents several advantages. From the observational point of view, the lines are easily observable, both in low- and high-metallicity regions, and less affected by reddening. Furthermore, their intensities can be measured relative to nearby hydrogen recombination lines, thus minimizing any effects resulting from uncertainties in flux calibration. On the theoretical side, their contribution to the cooling of the nebula becomes important at electron temperatures lower than in the case of the traditional  $O_{23}$  (previously called  $R_{23}$ ) and therefore its relation to oxygen abundance remains single-valued up to metallicities close to solar. Also, the fact that  $S_{23}$  is less dependent than  $O_{23}$  on ionization parameter reduces the scatter in the relation.



**Figure 4.** Relation between  $O_{23}$  and  $S_{23}$  for the objects in Table 1.



**Figure 5.** Variation of  $\log(S_{23}/O_{23})$  with galactic radius for M101, which actually mimics a logarithmic abundance gradient through the disc.

The application of this new metallicity calibration can provide more accurate abundance determinations for objects with  $\log O_{23}$  between 0.5 and 1.2, i.e. oxygen abundances between  $12 + \log(O/H) = 7.20$  ( $\approx 0.02$  times solar) and  $12 + \log(O/H) = 8.80$  ( $\approx 0.75$  times solar). This is the range of metallicities found in H II galaxies and in H II regions in irregular galaxies and outer galactic discs.

Regarding H II regions of higher metallicity, the composed parameter  $S_{23}/O_{23}$  can provide a better quantification of abundance gradients through galactic discs and might also hold the key to a future abundance calibration in this lower temperature regime.

#### ACKNOWLEDGMENTS

This work has been partially supported by DGICYT project PB-96-052. We thank Elena Terlevich and Bernard Pagel for a careful reading of the manuscript.

#### REFERENCES

- Allain D., Collin-Souffrin S., Joly M., Vigroux L., 1979, A&A, 78, 200  
Dennefeld M., Stasińska G., 1983, A&A, 118, 234



- Díaz A. I., 1998, *Ap&SS*, 263, 143  
Díaz A. I., Terlevich E., Pagel B. E. J., Vílchez J. M., Edmunds M. G., 1990, *Rev. Mex. Astron. Astrof.*, 21, 223  
Díaz A. I., Terlevich E., Vílchez J. M., Pagel B. E. J., Edmunds M. G., 1991, *MNRAS*, 253, 245  
Dopita M. A., Evans I. N., 1986, *ApJ*, 307, 431  
Edmunds M. G., Pagel B. E. J., 1984, *MNRAS*, 211, 507  
Garnett D. R., 1989, *ApJ*, 345, 282  
Garnett D. R., Shields G. A., Skillman E. D., Sagan S. P., Dufour R. J., 1997, *ApJ*, 489, 63  
González-Delgado R. M., Pérez E., 1996a, *MNRAS*, 278, 737  
González-Delgado R. M., Pérez E., 1996b, *MNRAS*, 281, 781  
González-Delgado R. M. et al., 1994, *ApJ*, 437, 239  
González-Delgado R. M., Pérez E., Díaz A. I., García-Vargas M. L., Terlevich E., Vílchez J. M., 1995, *ApJ*, 439, 604  
Henry R. B. C., Pagel B. E. J., Lasseter D. F., Chincarini G. L., 1992, *MNRAS*, 258, 321  
Henry R. B. C., Pagel B. E. J., Chincarini G. L., 1994, *MNRAS*, 266, 421  
Henry R. B. C., Balkowski C., Cayatte V., Edmunds M. G., Pagel B. E. J., 1996, *MNRAS*, 283, 635  
Kennicutt R. C., Garnett D. R., 1996, *ApJ*, 456, 504  
McCall L. M., Rybski P. M., Shields G. A., 1985, *ApJS*, 57, 1  
McGaugh S. S., 1991, *ApJ*, 380, 140  
Pagel B. E. J., Edmunds M. G., Blackwell D. E., Chun M. S., Smith G., 1979, *MNRAS*, 189, 95  
Pastoriza M. G., Dottori H. A., Terlevich E., Terlevich R., Díaz A. I., 1993, *MNRAS*, 260, 177  
Pérez-Olea D., 1996, PhD thesis, Univ. Autónoma de Madrid  
Shields G. A., Searle L., 1978, *ApJ*, 222, 281  
Skillman E. D., 1989, *ApJ*, 347, 883  
Skillman E. D., Kennicutt R. C., 1993, *ApJ*, 347, 875  
Skillman E. D., Terlevich R. J., Kennicutt R. C., Garnett D. R., Terlevich E., 1993, *ApJ*, 411, 655  
Vílchez J. M., Esteban C., 1996, *MNRAS*, 280, 720  
Vílchez J. M., Pagel B. E. J., Díaz A. I., Terlevich E., Edmunds M. G., 1988, *MNRAS*, 235, 633  
Zaritsky D., Kennicutt R. C., Huchra J. P., 1994, *ApJ*, 420, 87

This paper has been typeset from a  $\text{\TeX/L\AA\TeX}$  file prepared by the author.