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Abundances of the planetary nebula Hu 1-2[⋆]

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Abstract. The ISO and IUE spectra of the "elliptical" nebula Hu 1-2 are presented. These spectra are combined with new, high resolution spectra in the visual wavelength region to obtain a complete, extinction corrected, spectrum. The chemical composition of the nebula is then calculated and compared to previous determinations. The abundances determined are the lowest yet found in the analysis of ISO data. The evolutionary significance is discussed.

Key words. ISM: abundances – planetary nebulae: individual: Hu 1-2 – infrared: ISM – ISM: lines and bands

1. Introduction

The planetary nebula Hu 1-2 (PK 086.5-08.8) was discovered by Humason (1921). In his very short note he described the nebula as almost circular with a diameter of about 5″. This seems simple, but the nebula really has a much more complicated morphology, which is not always recognized. The nebula was classified as elliptical by Manchado et al. (1996) and these authors recognize that it has a larger diameter at very low flux levels. Hajian & Terzian (1996) have taken a snapshot with the VLA at 6 cm wavelength with sub-arcsec resolution and show that Hu 1-2 appears as a 6″ × 2″ boxlike structure oriented in the NE-SW direction. This boxlike structure appears to have a "waist", at least on one side, which is why the authors refer to it as "butterfly-like". This radio image contains about one quarter of the total flux of the nebula, and shows a hole in the center. This picture is corroborated by Sabbadin et al. (1987) who have taken an Hα photograph which shows the same boxlike structure oriented in the same direction and of the same size. They also have taken a deep photograph at the same wavelength showing that the nebula has a size of about 12″ × 8″ at the 5% level. In addition the corners of the box protrude, especially on the east and west side giving the nebula a "Z-like" appearance. The nebula has an outer extent at a very low level which appears to have a diameter of 20 to 25″. One should therefore be wary of using a morphological class "elliptical", since it is not typical of this class. It does not, however, belong to any of the other classes generally used.

Hu 1-2 is often referred to as a Type I nebula (e.g. Peimbert & Torres-Peimbert 1983). This is not primarily derived from the morphological structure; it refers principally to the high abundances of nitrogen and helium found in the nebula. We shall discuss the abundances later in this paper.

The distance of Hu 1-2 is not known, although most values given in the literature range between 1 and 2 kpc. Hajian & Terzian (1996) have attempted to find an expansion distance without success. They give a lower limit of 1.17 kpc. The nebula is 8.8° above the plane, corresponding to 150 to 300 pc at the above distances. The central star has been observed: Heap et al. (1990) report a visual magnitude of 17.76 observed with a seeing of 0.8″. This leads to a rather high Zanstra temperature which we discuss in a later section.

This article reports and analyses the spectrum in several wavelength regions. First the ISO far infrared spectrum is reported. Then a new high resolution spectrum in the visible is presented. These spectra are combined with the IUE ultraviolet observations to find the nebular abundances. The abundances found for this nebula are curious and we shall attempt a discussion of their evolutionary significance.

1.1. Advantages of the ISO spectrum

Combining the ISO SWS spectra of planetary nebulae with spectra of the nebula in other spectral regions allows an abundance determination which has several important advantages. These have been discussed in earlier papers (e.g.

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see Pottasch & Beintema 1999; Pottasch et al. 2000; or Bernard Salas et al. 2001).

The most important advantage is that the infrared lines originate from very low energy levels and thus give an abundance which is not sensitive to the temperature in the nebula, nor to possible temperature fluctuations. Furthermore, when a line originating from a high-lying energy level in the same ion is observed, it is possible to determine an effective temperature at which the lines of that particular ion are formed. When the effective temperature for many ions can be determined, it is possible to make a plot of effective temperature against ionization potential, which can be interpolated to determine the effective temperature for ions for which only lines originating from a high energy level are observed. Use of an effective electron temperature takes into account the fact that ions are formed in different regions of the nebula. In this way possible temperature gradients and fluctuations may be taken into account.

Use of the ISO spectra have further advantages. One of them is that the number of observed ions used in the abundance analysis is approximately doubled, which removes the need for using large "Ionization Correction Factors", thus substantially lowering the uncertainty in the abundance. Another advantage is that the extinction in the infrared is almost negligible, eliminating the need to include large correction factors for extinction.

2. The spectrum of Hu 1-2

2.1. ISO observations

The ISO SWS observations were made with the SWS02 observing template (TDT 54001009) which gives good spectral resolution for a limited number of lines. This was supplemented by an SWS01 observation (TDT 35801255) for which the intensities are less good. The intensities of the lines found in the spectrum are shown in Table 1. The uncertainty of the stronger lines is about 20%. The measurements with the SWS02 template were centered at RA(2000) $21^{\rm h}33^{\rm m}08.2^{\rm s}$ and Dec(2000) $+39°38'09.7''$.

This is essentially the same position as that given by radio continuum measurements reported below. Because the diaphragm used was $14'' \times 20''$ below 12 μm and somewhat larger above this wavelength, essentially the entire nebula (at least 95%) was measured by the SWS02. The SWS01 measurement was made at a slightly different position: $8''$ lower in declination. It did not measure the entire nebula and the line fluxes are a factor of two lower than the SWS02 measurement. The SWS01 observations are not used in the analysis and not reported in Table 1. There is one exception to this: the [S IV] line was only measured in the SWS01 scan. The intensity given is scaled so that the other lines have the same intensity as in the SWS02 scan.

An LWS spectrum was also taken (TDT 35801256), but it is noisy. The only lines which could be measured with certainty were the [O I], [O III] and [C II]reported in Table 1. Two other lines were also measured, but because they are noisy they are given as upper limits. No correction for extinction is made for the intensities reported in the table.

Table 1. ISO observations of Hu 1-2 (in units of 10^{-13} erg cm^{-2} s^{-1}).

Ident.	$\lambda(\mu$m)	Flux	Ident.	$\lambda(\mu$m)	Flux
H I 5-4	4.052	10.1	[Ne III]	15.556	62.5
[Mg IV]	4.487	5.5	[Ne V]	24.318	293.9
[Ar VI]	4.529	21.6	[O IV]	25.891	549.
[Mg V]	5.610	34.6	[O III]	51.8	≤48.
[Ne VI]	7.653	73.0	[N III]	57.3	≤45.
[S IV]	10.551	126.	[O I]	63.2	22.7
[Ne II]	12.813	4.6	[O III]	88.4	34.8
[Ne V]	14.322	243.1	[C II]	157.7	5.2

2.2. Radio continuum measurements

The first 6 cm radio continuum measurement was that of Issacman (1984), who measured 334 mJy with the VLA at this wavelength. This was followed by the Green Bank survey at the same wavelength. Becker et al. (1991) gave a value of 97 mJy with an uncertainty of 15 mJy. These data were reworked by Gregory & Condon (1991) who find 100 mJy with an uncertainty of 13 mJy. A 21 cm survey with the VLA by Condon & Kaplan (1998) found 107.5 ± 3.2 mJy. The position measured by these latter authors is the same as the ISO SWS02 measurement. However because the nebula may be optically thick at 21 cm, this still does not make clear what the 6 cm flux density is.

To resolve the discrepancy of the earlier measurements, we have made a 1.5 hour measurement with the interferomerer in Westerbork. At a wavelength of 6.2 cm a flux density of 103.6 ± 2.1 mJy was found, at a position: RA(2000) $21^{\rm h}33^{\rm m}08.35^{\rm s}$ and Dec(2000) $+39°38'09.38''$. Very little spatial information is available since the nebula is almost a point source, although the source seems elongated at a position angle of 88.7°.

We conclude that the result reported by Issacman for this nebula at 6 cm is wrong, for a reason we do not know. We use the Westerbork result throughout the remainder of this paper.

2.3. Extinction

The observed 6 cm radio emission of 103.5 mJy leads to a total Hβ flux of 2.22×10^{-11} erg cm^{-2} s^{-1}. The observed Hβ is 6.2×10^{-12} (Cahn et al. 1992). The extinction is therefore $C = 0.554$. The observed Balmer decrement is consistent with this value: the Lick spectra (see below) give $C = 0.60$. Earlier values were similar: Peimbert & Torres-Peimbert (1987) give $C = 0.64$, Aller & Czyzak (1979) find $C = 0.61$, and Sabbadin et al. (1987) give $C = 0.55$. The Brα line give a slightly lower value of $C = 0.44$ using a value of electron temperature $T_{\rm e} = 17\,000$ K. An extinction value can be obtained from the ratio of the He II lines $\lambda1640/\lambda4686$, and this value is somewhat higher: $C = 0.74$. This could be because the IUE measurement (shown below) is missing some of the nebular flux (the IUE diaphragm is an ellipse $10'' \times 20''$), or because a somewhat different extinction law applies in the ultraviolet. In order to insure that there is no systematic misinterpretation of the ultraviolet data, it has been corrected by assuming that the ratio of the two He II lines $\lambda1640/\lambda4686$ has its theoretical value at $T_{\rm e}$ = 18 000 (Hummer & Storey 1987). This fixes the $\lambda1640$ Å intensity corrected for extinction. The remainder of the IUE lines are then corrected with respect to the $\lambda1640$ Å line.

We thus use $C = 0.60$ or $E_{B-V} = 0.41$. The Hβ intensity corrected for extinction is 2.22×10^{-11} erg cm^{-2} s^{-1} using the extinction law taken from Fluks et al. (1994).

2.4. The visual spectrum

The spectrum in the visual region has been taken with the Hamilton echelle spectrograph at Lick Observatory. Details of the spectrograph are described by Hyung (1994). Most of the obervations were taken with "a small CCD chip" in a series of observations centered at the northern blob in August 1991 and another series of observations centered at the central position in September 1992. The northern blob observations were supplemented by the 2 K CCD chip observations in August 2001. The wavelength range is roughly between $\lambda3700$ Å and $\lambda10\,000$ Å for all data sets. The resolution is so high that nebular line splitting is observed and the intensity of the red and blue component is given separately so that one may be able to find the physical conditions for the front and back of the expanding gas, as well as the total line intensity. The diaphragm is about $1.2'' \times 4''$, thus somewhat smaller than the nebula. The resulting spectrum is given in Table A.1 of the appendix.

The visual spectrum has earlier been measured by Peimbert & Torres-Peimbert (1987) at Kitt Peak, using a larger diaphragm: $3.8'' \times 12.4''$. They made 3 measurements, the first centered on the nebula, the second $4''$ to the north of the center and the third measurement $6''$ north. The first and second measurements saw roughly half of the nebula while the third measurement saw less than 4% of the nebula. These authors measure essentially from $\lambda3700$ Å to $\lambda7400$ Å. The spectral resolution is moderate and only the stronger lines are seen.

Line intensities have also been reported by Aller & Czyzak (1979). These authors have measured with an earlier "ITS" spectrograph at Lick Observatory, presumably with a diaphragm of $2'' \times 2''$ on the central part of the nebula. Their spectra cover the range from $\lambda3100$ Å to $\lambda8580$ Å, but the intensities below $\lambda3725$ Å are "only approximate". Again only the stronger lines are seen.

For the purpose of this paper we wish to have the spectrum of the entire nebula, because the infrared and ultraviolet spectra also are measurements of the entire nebula. In Table 2 we report the average fluxes measured by the various authors for the transitions which we will eventually use in our analysis. Column 1 of the table gives the wavelength, Col. 2 the identification, Col. 3 the average value of the present measurements, Cols. 4 the average value of the two brightest regions measured by Peimbert and Torres-Peimbert and Col. 5 are the measurements of Aller and Czyzak. Columns 3, 4 and 5 are all fluxes with respect to H$\beta = 100$ and all are corrected for reddening as given by the authors, i.e. c = 0.60, 0.65 and 0.61 respectively. The reason for not bringing them all to a common value of extinction was that they all adjusted their reddening value to give the same theoretical value of the Balmer decrement, so that any residual wavelength dependances in their spectra will be removed. In the last column the unreddened fluxes are given, normalized to the total H$\beta = 2.22 \times 10^{-11}$ erg cm^{-2} s^{-1}. An average value of the individual measurements is used, with our measurements given double weight.

2.5. The IUE ultraviolet spectrum

There are 17 IUE spectra, 11 low resolution and 6 high resolution spectra. All the low resolution spectra have been reduced with NEWSIPS and are given in the appendix as Table B.1. The average fluxes of all the low resolution spectra are given in the fourth column of Table 3 (labeled (2)). The third column of this table (labeled (1)) gives the fluxes taken from the high resolution measurements SWP 44662 and LWP 23709. The high resolution fluxes are lower than the low resolution fluxes. This is common to other nebulae measured with the IUE, but the difference is rather large for the SWP spectra. We will use the low resolution fluxes to obtain abundances since these measurements are repeatable; the high resolution fluxes will be used to obtain line ratios.

The nebular IUE line intensities which will be used in the determination of abundances are listed in the last column of Table 3. The correction for extinction was done as follows. It was assumed that the ratio of the He II lines $\lambda1640$ Å to $\lambda4686$ Å had the theoretical value (Hummer & Storey 1987). The remainder of the ultraviolet lines were corrected with respect to $\lambda1640$ Å using the extinction curves of Fluks et al. (1994). This has the advantage that the dependance on the precise value of the extinction coefficient is strongly reduced, since the correction with respect to $\lambda1640$ Å is small. The last column of this table gives the fluxes after correction for extinction in this manner. The effective value of extinction is slightly different because of this method: $C = 0.63$.

The last line in the table at $\lambda3425$ Å is not an IUE measurement but is taken from Rowlands et al. (1984).

3. Chemical composition of the nebula

The method of analysis is the same as used in the papers cited in the introduction. First the electron density and temperature as function of the ionization potential is determined. Then the ionic abundances are determined, using density and temperature appropriate for the ion under consideration, together with Eq. (1) (see Sect. 3.3). Then the element abundances are found for those elements in which a sufficient number of ionic abundances have been determined.

3.1. Electron density

The ions used to determine $N_{\rm e}$ are listed in the first column of Table 4. The ionization potential required to reach that ionization stage, and the wavelengths of the lines used, are given in Cols. 2 and 3. Note that the wavelength units are Å when 4 ciphers are given and microns when 3 ciphers are shown. The observed ratio of the lines is given in the fourth column; the corresponding $N_{\rm e}$ is given in the fifth column. The temperature used is discussed in the following section, but is unimportant

Table 2. Visual spectrum of Hu 1-2 (unreddened fluxes in units of 10^{-13} erg cm^{-2} s^{-1}).

λ (Å)	Ion	Fluxes (1)	(2)	(3)	Unred. Flux
3726	[O II]	31.4			69.7
3727	[O II]	14.9			33.1
3869	[Ne III]	78	82	82	177
4163	[K V]	0.16			0.36
4340	Hγ	48	47	48.5	107
4363	[O III]	23.5	19,1	22.5	51
4471	He I	3.3		3.1	7.1
4686	He II	81.2	89	93.5	191
4711	[Ar IV]	5.32			11.8
4724	[Ne IV]	1.27			2.82
4726	[Ne IV]	1.30			2.89
4740	[Ar IV]	6.15	5.8	7.2	14.0
4861	Hβ	100	100	100	132
5007	[O III]	762	780	744	1692
5192	[Ar III]	0.27			0.6
5309	[Ca V]	0.13			0.29
5518	[Cl II]	0.49	0.38		1.09
5538	[Cl II]	0.63	0.55		1.40
5755	[N II]	5.26	4.8	4.9	11.5
5876	He I	10.1	10	9.5	22.2
6102	[K IV]	0.32			0.71
6228	[K VI]	0.16			0.36
6312	[S III]	2.60			5.77
6563	Hα	294	284	283	637
6584	[N II]	184	187	156	409
6717	[S II]	5.46	4.9	5.0	12.1
6731	[S II]	9.61	8.95	8.3	21.3
7005	[Ar V]	3.43	2.4	3.78	7.55
7136	[Ar III]	10.9	10.5	11.1	24.2
7237	[Ar IV]	0.37	0.25		0.82
7319	[O II]	4.3			10.1
7330	[O II]	3.3			8.7
8045	[Cl IV]	0.87	0.85		1.93
8579	[Cl II]	0.16			0.36
9069	[S III]	13.7			30.4
9531	[S III]	32.0			71.0
9546	Pa8	1.71			3.8

(1) This paper, (2) Aller & Czyzak (1979), (3) Peimbert & Torres-Peimbert (1987).

Table 3. IUE spectrum of Hu 1-2.

λ (Å)	Ion	Fluxes (1)	(2)	Unred. (3)
1238$^{\dagger\,*}$	N V	5.0	11.5	53.9
1400†	O IV]		5.0	12.7
1483†	N IV]	4.3	22.1	56.9
1487	N IV]	5.7		
1550$^{\dagger\,*}$	C IV	40.0	62.	158.
1640	He II	46.5	55.	134.
1665$^{\dagger\,*}$	O III]	3.5	4.2	10.
1750†	N III]		17.	37.9
1884	Si III]	1.3:	3.5	8.3
1906	C III]	20.2		
1909†	C III]	14.1	40.	98.0
2325†	C II]		6.0	18.6
2422†	[Ne IV]	10.9	21.	47.2
2425	[Ne IV]	9.3		
2513	He II		2.2	4.04
2734	He II	3.8	4.5	5.5
2784	[Mg V]	3.5	4.0	4.7
2929	[Mg V]	1.4		1.4
2979	[Ne V]		2.6:	2.6
3204	He II		14.2	11.7
3425	[Ne V]		63.	40.3

(1) High dispersion – all flux units 10^{-13} erg cm^{-2} s^{-1}.
(2) Low resolution – all flux units 10^{-13} erg cm^{-2} s^{-1}.
(3) Average fluxes corrected for extinction as discussed in the text – all flux units 10^{-12} erg cm^{-2} s^{-1}.
† The fluxes given in Cols. (2) and (3) are for the entire multiplet.
* The fluxes given in Col. (1) are for the entire multiplet.

since these line ratios are essentially determined by the density.

There is no indication that the electron density varies with ionization potential in a systematic way. The electron density appears to be between 3000 and 9000 cm^{-3}. It is interesting to compare this value of the density with the RMS density found from the Hβ line. This depends on the distance of the nebula which isn't accurately known, and on the angular size of the nebula. For this calculation we shall use a distance of 1.5 kpc (Acker et al. 1992). A sphere of diameter of 8.2$''$ will represent the nebula. The Hβ flux has been given above and the electron temperature will be discussed below. We obtain a value of 5100 cm^{-3}. This value is uncertain because the distance is not well known. However the RMS density varies only as the square root of the distance. It is therefore likely that the similarity of these values to the forbidden line densities is real. This probably indicates inhomogeneities do not play a dominant role in determining the density. We will use a density of 5000 cm^{-3} in further discussion of the abundances.

3.2. Electron temperature

A number of ions have lines originating from energy levels far enough apart that their ratio is sensitive to the electron temperature. These are listed in Table 5, which is arranged similarly to the previous table. The electron temperature are computed with the density given above and remains roughly constant as a function of ionization potential, at least for ionization potentials between 20 eV and 60 eV. The two ions with low ionization potential, O I and N II, show a substantially lower electron temperature. These ions are formed in the outer regions of the nebula. Other ions formed in the low temperature regions probably are S II, C II and O II. At ionization potentials above 20 eV the temperature has risen to at least 17 000 K and then remains roughly constant at about 18 000 K until 60 or 70 eV. For the higher ionization potentials the increase continues. For our purpose these temperatures do not have to be presicely fixed because lines originating from these high ionization states all occur in the far infrared where the electron collision rate is insensitive to the temperature.

Table 4. Electron density indicators.

Ion	Ioniz. pot. (eV)	Lines used	Observed ratio	N_e (cm^{-3})
S II	10.4	6731/6716	1.72	5 000
O II	13.6	3726/3729	2.10	9 000
Cl III	23.8	5538/5518	1.40	7 200
C III	24.4	1907/1909	1.43	3 000
Ar IV	40.7	4740/4711	1.16	3 000
Ne IV	63.5	2425/2422	0.85	7 000 (4 000)†
Ne V	97.1	24.3/14.3	1.21	very low

† from Keenan et al. (1998).

Table 5. Electron temperature indicators.

Ion	Ioniz. pot. (eV)	Lines used	Observed ratio	T_e (K)
O I	13.6	5577/6300	0.027:	13 000 (11 500)†
N II	14.5	5755/6584	0.0303	12 500
Ar III	27.6	5192/7136	0.0235	17 300
O III	35.1	4363/5007	0.0305	18 600
O III	35.1	1663/5007	0.0591	16 200
Ne III	41.0	3869/15.5	2.83	17 000
O IV	54.9	1400/25.9	2.31	18 000
Ne IV	63.5	2424/4725	82.7	19 000 (18 600)‡
Ne V	97.1	3425/24.3	1.39	22 000
Mg V	109.	2783/5.61	1.35	24 000

† From Keenan et al. (1995).
‡ From Keenan et al. (1998).

In the analysis of other nebulae the temperature found from the [Ne III] lines was often lower than what would be expected from the ions with a similar ionization potential. This does not appear to be the case for Hu 1-2.

3.3. Ionic and element abundances

The ionic abundances have been determined using the following equation:

$$\frac{N_{\rm ion}}{N_{\rm p}} = \frac{I_{\rm ion}}{I_{{\rm H}_\beta}} N_{\rm e} \frac{\lambda_{\rm ul}}{\lambda_{{\rm H}_\beta}} \frac{\alpha_{{\rm H}_\beta}}{A_{\rm ul}} \left(\frac{N_{\rm u}}{N_{\rm ion}}\right)^{-1} \tag{1}$$

where $I_{\rm ion}/I_{{\rm H}_\beta}$ is the measured intensity of the ionic line compared to Hβ, $N_{\rm p}$ is the density of ionized hydrogen, $\lambda_{\rm ul}$ is the wavelength of this line, $\lambda_{{\rm H}_\beta}$ is the wavelength of Hβ, $\alpha_{{\rm H}_\beta}$ is the effective recombination coefficient for Hβ, $A_{\rm ul}$ is the Einstein spontaneous transition rate for the line, and $N_{\rm u}/N_{\rm ion}$ is the ratio of the population of the level from which the line originates to the total population of the ion. This ratio has been determined using a five level atom.

3.4. Abundances in Hu 1-2

The results are given in Table 6, where the first column lists the ion concerned, and the second column the line(s) used for the abundance determination. The third column gives the intensity of the line used relative to Hβ. The fourth column gives the temperature used to determine the ionic abundances, interpolated from Table 5. The ionic abundances are shown in the fifth column, where a density of 5000 cm^{-3} has been used, although the exact value of the density is usually unimportant. The sixth column gives the Ionization Correction Factor (ICF). This has been determined empirically. Notice that the ICF is usually small, less than a factor 1.5, and the element abundances, given in the last column, are probably well determined.

4. Comparison with other abundance determinations

Table 7 shows a comparison of our abundances with the most important determinations in the past 20 years. There is reasonable agreement, usually to within a factor of two. The nebula appears to have similar amounts of carbon and oxygen, which has also been found by other authors. The nitrogen is higher than either carbon or oxygen, which agrees with the earlier determinations.

The helium abundance is slightly lower than other determinations. Only the λ5875 Å line was used in the determination of He$^+$ because it is felt that the theoretical determination of this line is the most reliable. In this case the use of λ4471 Å would not have changed the result.

4.1. Errors

It would be interesting to determine the errors in the abundance analysis. Unfortunately this is difficult to do. The reason for this is the following. The error can occur at several stages in the determination. An error can occur in the intensity determination and this can be specified: it is probably less than 30% except for the very weak lines where it may reach a factor of two. An error may occur in correcting for the extinction, either because the extinction is incorrect or the average reddening law is not applicable. We have tried to minimize this possibility by making use of known atomic constants to relate the various parts of the spectrum. Thus the ratio of Brα to Hβ is an atomic constant. The ratio of the infrared spectrum to the visible spectrum is fixed in this way. Similarly, the fixed ratio of the He II lines connects the visible to the ultraviolet spectrum.

A further error is introduced by the correction for unseen stages of ionization. This varies with the element, but is usually small because of the very many ionization stages observed. Thus for neon all but neutral neon is observed, so that the error will be small. This is also true for sulfur, argon, oxygen and nitrogen where the higher stages of ionization which are not observed, contribute very little to the abundance.

There is also an error due to uncertainties in the collisional cross-section and the transition probabilities. The former is estimated at 25% and the latter is smaller. One might think that when comparing nebulae this error will disappear, since the same error is made in all nebulae. This is partly true, but because the contribution of a given ion varies with the nebula,

Table 6. Ionic concentrations and chemical abundances in Hu 1-2. Wavelength in Angstrom for all values of λ above 1000, otherwise in μm.

Ion	λ	Flux	T_e	N_{ion}/N_p	ICF	$N_{el.}/N_p$
He^{+}	5875	0.101	15 000	0.051		
He^{++}	4686	0.85	18 000	0.076	1	0.127
C^{+}	2325	0.838	12 000	5.45(–5)		
C^{++}	1909	4.41	16 000	5.71(–5)		
C^{+3}	1548	7.12	18 500	3.07(–5)	1.14	1.62(−4)
N^{+}	6584	1.84	12 500	2.47(–5)		
N^{++}	1750	1.71	17 300	5.97(–5)		
N^{+3}	1487	2.56	17 500	7.74(–5)		
N^{+4}	1238	2.43	19 300	2.82(–5)	1	1.9(−4)
O^{+}	3727	0.598	12 000	2.37(–5)		
O^{++}	5007	7.62	17 800	5.80(–5)		
O^{+3}	25.9	2.48	18 800	5.14(–5)	1.18	1.57(−4)
Ne^{+}	12.8	0.0207	15 000	2.28(–6)		
Ne^{++}	15.5	0.282	18 200	1.42(–5)		
Ne^{+3}	2425	2.13	19 000	1.94(–5)		
Ne^{+4}	24.3	1.324	20 000	1.35(–5)		
Ne^{+5}	7.65	0.329	21 000	7.7(–7)	1	4.9(−5)
Mg^{+3}	4.49	0.0248	19 000	6.8(–7)		
Mg^{+4}	5.61	0.156	25 000	2.69(–6)	2	6.7(−6)
S^{+}	6731	0.096	12 000	4.8(–7)		
S^{++}	6312	0.026	16 000	1.1(–6)		
S^{++}	9531	0.28	16 000	8.5(–7)		
S^{+3}	10.5	0.508	17 500	1.34(–6)	1.5	4.2(−6)
Ar^{++}	7136	0.11	17 000	3.56(–7)		
Ar^{+3}	4740	0.063	18 000	3.3(–7)		
Ar^{+4}	7005	0.109	18 500	1.95(–7)		
Ar^{+5}	4.53	0.097	20 000	9.4(–8)	1.2	1.1(−6)
Cl^{+}	8579	1.62(–3)	12 000	1.12(–8)		
Cl^{++}	5538	6.3(–3)	16 000	2.6(–8)		
Cl^{+3}	8046	8.7(–3)	18 000	2.56(–8)	1.7	1.1(−7)
K^{+3}	6102	3.2(–3)	17 000	8.35(–9)		
K^{+5}	6228	1.6(–3)	19 000	2.1(–9)	2.8	3.0(−8)
Ca^{+4}	5309	1.4(–3)	18 000	7.8(–9)		

Intensities given with respect to $H\beta = 1$. A(–B) denotes $A \times 10^{-B}$.

some unspecifiable error will remain. In a previous article this has been estimated as 30% (Pottasch et al. 2001), but this may be an overestimate.

5. The central star

As mentioned in Sect. 1, this nebula is excited by a central star whose spectrum is not known. The visual magnitude of 17.76 measured by Heap et al. (1990) is considered to be more reliable than the slightly brighter measurement of Kaler & Jacoby (1991) because the seeing was so much better in the first measurement. This leads to a visual continuum flux of 9.35×10^{-12} erg cm^{-2} s^{-1} after correction for extinction. Using the Hβ flux given above, the hydrogen Zanstra temperature (T_z(H)) is about 100 000 K. The ionized helium Zanstra temperature is somewhat higher, T_z(HeII) = 145 000 K. This may indicate that the nebula is thin to radiation which ionizes hydrogen. The "Stoy" or Energy Balance temperature can also be found from the above data. The value of the ratio of "forbidden line emission" (including all collisionally excited emission) to Hβ is about 51.2. There is at least a 10% error on this number however, since it is difficult to estimate the strength of unobserved lines. With the assumption that the nebula is thin to hydrogen ionizing radiation and thick to doubly ionized helium radiation (case I of Preite-Martinez & Pottasch 1983) this leads to an energy balance temperature (T_{EB}) of 130 000 K. A value of T_{star} = 140 000 K is consistent with these data, and is probably sufficient to explain the presence of ions of Mg^{+4} and Ne^{+5} in the nebula.

Table 7. Comparison of abundances in Hu 1-2.

Elem.	Present	PTP(1)	AC(2)	SCT(3)	M(4)
He	0.127	0.147	0.158	0.157	0.154
C(−4)	1.62		1.2		1.2
N(−4)	1.9	2.2	3.2	6.5	1.5
O(−4)	1.57	1.6	1.1	0.31	1.1
S(−6)	4.2		3.0	3.1	7.8
Ar(−6)	1.1	0.79	1.6		0.87
Ne(−5)	4.9	3.6	6.7	4.4	5.9
Cl(−7)	1.1		1.5		

(1) Peimbert & Torres-Peimbert (1987); (2) Aller & Czyzak (1979); (3) Sabbadin et al. (1987); (4) Malkov (1998).

6. Recombination line radiation

Several permitted lines of nitrogen, oxygen and carbon are seen in the visual spectrum. About half of these lines are formed by the Bowen fluorescence mechanism and cannot be used for determining ionic abundances. These are the N III lines 4097.2, 4103.3, 4634.0, and 4640.6 Å, as well as the O III line at 3759.8 Å. We can attempt to obtain recombination line abundances of O^{++} using the line at 4649.1 Å of O II. (Lines of the same multiplet at 4641.7 Å and 4651.0 Å have been ignored because of probable blending with N III and C III lines.) Using the effective recombination coefficients given by Storey (1994), derived assuming LS coupling, gives an abundance of $O^{++}/H = 7.7 \times 10^{-5}$ which may be compared to the collisional abundance given in Table 6 of 5.8×10^{-5}. In the same way, the V1 multiplet of C III (4647.3 and the blend at 4651.0 Å) yield a recombination line abundance of $C^{+3}/H = 5 \times 10^{-5}$ (compare the collisional abundance of 3.1×10^{-5}).

The only other usable recombination line is the C II line at 4267 Å. This line has been measured by Aller & Czyzak (1979) and by Peimbert & Torres-Peimbert (1987). The latter authors give an uncertain intensity ratio $\lambda 4267/H\beta = 2 \times 10^{-3}$, the former authors a somewhat higher value. Our Lick measurements barely detect this line in the 1991 northern observations with a value of $\lambda 4267/H\beta = 1.1 \times 10^{-3}$. This may only be an upper limit. This value yields a recombination line abundance of $C^{+2}/H = 1 \times 10^{-4}$, but may be too high. For comparison the collisional abundance is 5.7×10^{-5}, which is essentially equal to the recombination line abundance, considering the rather large measurement errors in the latter.

Since measuring the intensity of these faint lines is difficult, the errors are larger than for the strong lines. Within these errors there is no strong evidence for a difference between the abundances obtained from the recombination lines and from the collisional lines for this nebula.

7. Discussion

Of the 12 nebulae whose abundance has been determined with the help of ISO measurements, Hu 1-2 has by far the lowest abundance. This is shown in Table 8 where a comparison is made between the average abundances for eleven nebulae (nine have been published, plus NGC 6543 and NGC 6153), shown in the second column, with Hu 1-2 in the third column. The abundances in Hu 1-2 are consistently a factor of 3 lower for all elements.

In order to put this in perspective the abundances in two of the best studied HII regions in the LMC are also given in the table. In the fourth column the abundances in N44C are given. These are taken from Garnett et al. (2000) who combined ground based and HST spectroscopy (including the ultraviolet) in a careful study of this nebula. In the fifth column the abundances in the 30 Doradus nebula are shown, from the study of Vermeij & vans der Hulst (2003). The abundances of oxygen, neon, sulfur and argon are, within the measurement errors, the same for Hu 1-2 as for the LMC HII regions. These so-called primary elements are not produced in the planetary nebula central star in the course of its evolution, but reflect the abundances in the star at the time of its formation. Since the abundance of the interstellar material out of which stars are formed increases with time, these low abundances observed in Hu 1-2 indicate that the central star is old, considerably older than the central stars of the other PNe observed. The central star therefore took a much longer time to reach the planetary nebula stage: this would indicate that it is a low mass star where the evolution proceeds much more slowly. Because stars of about 1 solar mass formed at an early stage in the history of the galaxy are now reaching the PN stage, we conclude that the central star of Hu 1-2 was originally a low mass star with a mass close to, or slightly greater than 1 solar mass.

But Hu 1-2 has a nitrogen abundance N/O greater than unity and a high He/H ratio as well. Because of this the nebula is classed as Type I. The nitrogen and helium have been formed in the course of the evolution of the central star. It is thought that the large production of these elements indicates that the central star has a high mass (e.g. Peimbert & Torres-Peimbert 1983) give a minimum mass of 2.4 solar masses). These two mass determinations are incompatible and indicate a hiatus in the understanding of evolution. One should be very careful in the assumption that a Type I nebula is formed from a high mass star: it may not be true.

That current stellar evolution models fail to predict sufficient nitrogen enrichment for stars of rather low stellar mass has been suggested earlier. e.g. Stasinska & Tylenda (1990). The present evidence strengthens these suggestions considerably.

8. Summary and conclusion

1) New observations of Hu 1-2 in three spectral regions are presented. In the far infrared ISO measurements between 4 μm and 157 μm are given. In the visual, high resolution spectra from 3726 Å to 10124 Å are presented, and in the ultraviolet newly reduced IUE measurements are shown. A new Westerbork 6 cm total flux density measurement has also been made.

2) These observations are sufficient to allow an investigation of the electron temperature structure of the nebula, which is found to decrease from about 24 000 K at the center to about 12 500 K in the outer regions.

3) The abundances of 10 elements (with respect to hydrogen) has been found, with higher accuracy than previous determinations. This is due principally to the use of many ions having lines which are insensitive to electron temperature, and the use of a better determined temperature structure for the remainder of the ions. The many lines used also minimize corrections needed for “missing” ionization stages.

4) No evidence is found that abundances found from recombination lines are different than those lines which are collisionally excited in this nebula.

5) The central star is quite hot, approximately $T_{\rm star}$ = 140 000 K.

6) The abundances of the primary elements, O, S, Ne and Ar are lower than found in other PN studied using ISO data. However these abundances agree with those found for LMC HII regions. From this it is concluded that the central star of Hu 1-2 was formed very long ago, i.e. it is a very old star. It is also of low mass, since it has taken so long for it to reach the PN stage.

7) The nebula is found to have a very high nitrogen abundance, even higher than oxygen. Such a high abundance must have occurred in the course of the star’s evolution. Such a high nitrogen production is predicted to occur only if the mass of the star is higher than 2.4 solar masses. But this is in contradiction with the previous conclusion that the star must have a low mass. This indicates that at least one of these arguments is incorrect. It may be that the evolution theory should be reconsidered.

Table 8. Comparison of abundances in Hu 1-2.

Element	PN Ave.	Hu 1-2	LMC N44C	30 Dor.
C(−4)	3.9	1.6	0.69	
N(−4)	3.6	1.9	0.133	0.05–0.07
O(−4)	4.4	1.57	2.1	1.8
Ne(−5)	16.	4.9	6.0	7.0
S(−6)	10.	4.2	4.0	6.5
Ar(−6)	4.2	1.1	1.4	1.0

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Appendix A: Visual lines

The complete measurements described in Sect. 2.4 taken with the Hamilton echelle spectrograph at Lick Observatory are

Table A.1. Optical spectrum of Hu 1-2 (North and Center).

			North			Center		
$\lambda_{\rm obs}$	Ion	I(2001)	$I(R+B)$	$I(R)$	$I(B)$	$I(R+B)$	$I(R)$	$I(B)$
3726.07	[O II]	30.54	31.94	39.12				
3728.83	[O II]	14.42	15.45	19.05	5.648	14.94	12.35	19.22
3759.79	O III		1.927	2.212	1.140	2.14	1.75	2.80
3835.23	H I	6.791	5.296			6.66	5.82	8.04
3868.74	[Ne III]	68.67	70.27	84.67		86.90	73.02	109.8
3888.68	He I	21.86	13.36		4.214	18.89		
3967.45	[Ne III]	25.83	21.68	26.37	9.080	27.57	22.74	35.55
3968.31	[Ne III]				71.61			
3970.01	H ϵ	16.97	11.55	12.29	9.48	16.24	14.91	18.45
4026.22	He I	2.327	1.785	1.573	2.359	1.06	0.94	1.25
4068.63	[S II]	2.991	3.302	3.997	1.405	3.41	2.74	4.52
4076.36	[S II]		1.193	1.412	0.593	0.99	0.70	1.46
4097.17	N III, O II			0.771		0.75	0.64	0.95
4101.68	H δ	23.51	20.01	21.15	16.00	25.49	23.47	28.82
4103.30	N III		0.394	0.430	0.299			
4199.66	He II	1.334	1.186	1.112	1.384	1.48	1.20	1.95
4338.52	He II	3.188	2.342	2.170	2.815			
4340.43	H γ	43.58	49.13	48.79	49.81	48.19	47.49	49.37
4357.91	O II	1.426						
4363.16	[O III]	19.19	25.65	27.61	20.28	24.57	22.34	28.25
4471.51	He I	3.228	2.679	4.570	2.454	3.85	3.53	4.38
4541.43	He II	3.186	3.142	3.193	2.973	2.94	2.95	2.92
4634.09	N III		0.393	0.459	0.212	0.35	0.27	0.49
4640.66	N III	0.872	1.249	1.418	0.397	1.04	0.97	1.16
4641.79	N III, O II			0.020				
4647.35	C III		0.106			0.34		
4649.14	O II		0.039					
4651.05	C III, O II		0.096					
4658.21	C IV, [Fe III]		0.220	0.214	0.235	0.28	0.28	0.29
4685.58	He II	81.34	73.84	74.52	71.66	88.76	87.65	90.60
4711.28	[Ar IV]	5.763	4.525	4.433	4.771	5.65	4.98	6.77
4714.15	[Ne IV]	1.022	1.397	0.836	3.022	0.80	0.81	0.79
4724.06	[Ne IV]		1.355	1.318	1.452	1.21	1.08	1.42
4725.47	[Ne IV]		1.609	1.516	1.861	1.02	0.83	1.33
4740.09	[Ar IV]	6.261	6.511	6.105	7.615	5.45	5.19	5.88
4859.08	He II		4.585	4.490	5.524	3.02		
4861.29	H β	100.0	100.0	100.0	100.0	100.0	100.0	100.0
4922.00	He I		1.553	1.384	1.784		0.99	
4958.99	[O III]	244.4	221.4	241.60	166.4	279.0	303.5	238.5
5006.88	[O III]	745.7	717.0	735.4	669.2	823.3	874.6	738.6
5015.81	He I	1.212	2.236	2.418	1.708	1.63	1.62	1.65
5198.10	[N I]	1.034	1.697	1.899	1.144	1.45	1.38	1.57
5200.47	[N I]		1.107	1.242	0.740	0.96	0.96	0.96
5308.79	[Ca V]		0.171	0.202	0.157	0.08		
5323.05	[Cl IV]		0.111	0.151	0.170	0.16	0.17	0.15
5411.30	He II	7.131	5.945	6.444	5.335	5.44	5.98	4.54
5517.73	[Cl III]		0.475	0.477	0.433	0.50	0.44	0.60
5537.89	[Cl III]	0.593	0.594	0.656	0.507	0.71	0.73	0.69
5754.71	[N II]	4.421	5.670	7.220	2.816	5.67	6.12	4.93
5875.75	He I	7.351	10.06	11.73	4.846	11.51	12.67	9.58
6101.59	[K IV]		0.348	0.259	0.267	0.30	0.28	0.35
6227.68	[K VI]		0.232			0.10		
6300.38	[O I]	5.586	6.670	8.494	1.691			
6312.00	[S III]	3.244		3.484	2.366	2.14	1.80	2.70
6363.64	[O I]	2.072	2.116	2.719	0.838	2.81	2.80	2.82
6434.56	[Ar V]	1.855	1.322	1.242	1.192		3.04	
6548.22	[N II]	40.98	58.96	70.89	27.52	71.76	78.81	60.12
6559.92	He II		10.88	10.85	10.95	14.72	16.66	11.51
6562.81	H α	281.4	268.1	275.6	247.4	334.7	349.4	310.4

shown in Table A1. The column labeled I(2001) gives the measurements made in August 2001 in the northern part of the nebula. $I(R)$ and $I(B)$ are intensities from the red and blue-shifted line profiles, while $I(R+B)$ are the combined intensities.

Table A.1. continued.

			North			Center		
$\lambda_{\rm obs}$	Ion	I(2001)	$I(R+B)$	$I(R)$	$I(B)$	$I(R+B)$	$I(R)$	$I(B)$
6583.52	[N II]	136.3	171.1	213.0	60.49	241.7	256.3	217.4
6678.18	He I	2.410	2.438	3.048	0.774			
6716.67	[S II]	4.778	5.422	6.211	3.252	6.17	6.57	5.50
6730.72	[S II]	7.467	9.423	11.020	5.107	11.92	12.05	11.70
7005.27	[Ar V]	4.161	2.686	2.577	1.858			
7064.85	He I	4.076	5.096	6.071	2.439	6.37	6.61	5.98
7135.82	[Ar III]	9.631	10.96	12.15	7.703	11.81	12.10	11.34
7319.00	[O II]	4.552				4.24	5.75	1.66
7330.14	[O II]	3.968				3.18	2.93	3.58
7529.66	[Cl IV]		0.463	0.478	0.431	0.48	0.45	0.53
7592.39	He II	1.480	1.138	1.072	1.259	1.10	0.95	1.35
7751.01	[Ar III]	2.669	2.180	2.603	1.046			
8045.50	[Cl IV]	0.895	0.869	0.863	0.879	0.84	0.80	0.91
8236.38	He II	2.289	1.457	1.547	1.196			
8578.85	[Cl II]		0.160					
9014.60	H I	1.386	0.981					
9069.04	[S III]	12.26	13.38	14.14	11.26	14.86	13.87	16.50
9227.98	He I	1.732	1.609	1.769	1.835	1.71	1.69	1.74
9530.59	[S III]	25.24	21.54	24.67	12.98	36.97	33.48	42.72
9545.96	H I	1.746	0.940	1.018	0.544			
10048.95	H I	2.952	2.271	2.204	1.660			
10123.16	He II	15.25	9.776	11.22	5.863			

See Hyung (1994) for the identifications and references therein. Interstellar extinction corrected intensities are all given on the scale of $I(\mathrm{H}\beta) = 100$ ($C = 0.60$). I(2001): intensities of August 2001 observation (at North); $I(R)$ and $I(B)$ are intensities from the red and blue-shifted line profiles, respectively, while $I(R+B)$ are intensities combined from both profiles.

Table B.1. Ultraviolet IUE spectrum of Hu 1-2 (Low resolution).

			Flux 10^{-13} ergs cm^{-2} s^{-1}					
$\lambda_{\rm obs}$	$\lambda_{\rm lab}$	Ion	1992(1)	1991(2)	1981(3)	1981(4)	1979(5)	1978(6)
1238.4	1238/1242	N V	7.9	(20.1)	11.5	11.9	13 8	10.4
1399.6	1400/1402	O IV	8.2		7.0	8.8	8.6	9.1
1483.0	1483/1486	N IV	22.2	37.3	21.4	19.5	23.3	22.0
1546.7	1548/1551	C IV	56.8	64.1	62.3	62.0	62.3	64.7
1638.7	1640	He II	47.7	45.9	55.6^s	54.2	53.8	67.2
1663.1	1661/1666	O III	3.5		4.5	4.2	6.2	3.4
1747.6	1746/1752	N III	17.2	17.0	12.6	13.5	15.4	18.2
1884.0	1883	Si III	2.2	5.1	1.2	1.6	(3.2)	3.8
1906.7	1906/1909	C III	25.4	35.9	37.2^s	40.9	39.5	48.5
2327.9	2324/2328	C II	7.2	6.5				5.5
2426.1	2422/2425	Ne IV	20.0	23.6		18.2	18.8	24.6
2513.3	2511	He II	2.0	2.5				2.1
2734.9	2734	He II	5.0	3.3		5.3	6.6	3.7
2784.2	2783	Mg V	5.1	2.4		4.0	3.9	
3130.9	3133	O III	10.1	9.7		10.8	9.1	8.4

(1) SWP 46578, LWP 24584, on center of light; (2) SWP 42044, LWP 20788; (3) SWP 13945; (4) SWP 13339, LWR 8851; (5) SWP 7258, LWR 6254; (6) SWP 3658, LWR 3221; ^{s} possibly saturated.

Appendix B: Ultraviolet (IUE) lines

The individual IUE low resolution spectra are shown in Table B.1, as described in Sect. 2.5. They have not been corrected for extinction. The average values as well as the high resolution measurements have already been given in Table 3.

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