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NEBULAR KINEMATICS OF PLANETARY NEBULAE AS TESTS OF POSSIBLE DIFFERENCES OF DISTRIBUTION OF PERMITTED AND FORBIDDEN EMISSION LINES

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RESUMEN

En las nebulosas gaseosas la abundancias químicas de los elementos pesados que se derivan de las líneas de recombinación resultan sistemáticamente más altas que las que se derivan de las líneas excitadas colisionalmente. Las explicaciones que se han ofrecido para obtener soluciones compatibles han sido atribuir estas diferencias al efecto de inhomogeneidades en la temperatura, o atribuirlas a la presencia de nudos densos de material enriquecido. Nosotros hemos obtenido observaciones de rendija larga en algunas nebulosas planetarias para tratar de resolver esta controversia. Presentamos resultados preliminares para NGC 6543.

ABSTRACT

In gaseous nebulae the abundances of heavy elements derived from recombination lines are systematically higher than those derived from collisionally excited lines. The possible explanations to obtain compatible solutions are: either to attribute the difference to the presence of temperature inhomogeneities or to the presence of dense clumps of colder enriched material. We have obtained long slit echelle spectrograms in several planetary nebulae to try to shed light on this topic. We present preliminary results for NGC 6543.

Key Words: H II regions — planetary nebulae

1. INTRODUCTION

There is a standing controversy on the explanation of the different chemical abundances of the heavy elements derived in planetary nebulae from optical recombination lines (ORL) and those derived from forbidden lines, or collisionally excited lines (CEL). There are two schools of thought to solve this controversy. I. That the nebular material is a chemically homogeneous medium with strong temperature and density variations, where the optical recombination lines are predominantly produced in the low temperature regions, and the collisionally excited lines are predominantly produced in the high temperature regions. II. Alternatively that many PNe are chemically inhomogeneous (e.g. Liu 2006, and references therein). In the two-abundance nebular model, there are two components: a) the low density component, that has most of the mass and is relatively hot, emits practically all the intensity of the H lines and of the forbidden lines in the visual and the UV, and part of the intensity of the He I lines, and b) the high density component, that has only a small fraction of the total mass, is relatively cool, H-poor, and rich in heavy elements, and emits part of the He I and of the recombination line intensities of the heavy elements but practically no H and no heavy element collisionally excited lines. In this paper we will discuss briefly these two points of view, and the evidence available to support them. We further propose to analyze this issue by studying the kinematics of the emission lines from both processes in several planetary nebulae. We are interested in determining whether in the two chemically different scenarios there are regions in space where the dense knots would congregate, or whether the dense matter has different kinematical behavior. This issue could be studied by comparing the collisionally excited emission lines and the optical recombination lines of the same species and ionization, namely for oxygen lines. For this purpose we have compared the emission lines in NGC 6543 to try to find any systematic differences in behavior.

2. CHEMICALLY HOMOGENEOUS MEDIUM

Reviews on the presence of temperature variations in PNe have been presented by Peimbert & Peimbert (2006), Esteban et al. (2002), Liu (2003, 2006), and Torres-Peimbert & Peimbert (2003). 1D static chemically homogeneous photoionization models can fit one third of the well observed PNe, but the

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remaining object show temperature variations that are considerably larger than predicted.

2.1. *Temperature determinations*

Peimbert (1967, 1971) found that the temperatures derived from the $I(4363)/I(5007)$ ratio, T_e([O III]), are considerably larger than the temperatures derived from the Balmer continuum to a Balmer recombination line ratio, T_e(Balmer); he interpreted this result as a consequence of the existence of temperature inhomogeneities over the observed volume. To study this problem, Peimbert proposed a formalism that depends on the use of the average temperature, T_0, and the mean square temperature fluctuation, t^2, as defined by the following expressions

$$T_0(N_e, N_i) = \frac{\int T_e(\mathbf{r}) N_e(\mathbf{r}) N_i(\mathbf{r}) dV}{\int N_e(\mathbf{r}) N_i(\mathbf{r}) dV}, \tag{1}$$

and

$$t^2 = \frac{\int (T_e - T_0)^2 N_e N_i dV}{T_0^2 \int N_e N_i dV}, \tag{2}$$

from this approximation it follows directly that the forbidden lines (collisionally excited emission lines, or CEL) are predominantly produced in the high temperature zones, while the recombination emission lines of the same species are predominantly produced in the relatively colder zones within the line of sight. In the presence of temperature fluctuations along the observed volume there is a standing difference between the heavy element abundances derived from the two sets of lines; the difference being larger for the case of larger temperature fluctuations t^2 (c.f. Peimbert 1967; Peimbert & Costero 1969; Ruiz et al. 2003; Peimbert et al. 2004).

The large differences between T_e([O III]) and T_e(Balmer) have been confirmed by several authors for a large number of PNe (e.g. Liu & Danziger 1993; Zhang, Liu, & Wesson 2004).

Peimbert, Storey, & Torres-Peimbert (1993) based on the computations by Storey (1994) were the first to obtain larger O^{++}/H^+ values from oxygen recombination lines than from collisionally excited lines under the assumptions of $t^2 = 0.000$ and of chemical homogeneity. Most PNe show this difference which has been usually called the abundance discrepancy factor defined by: ADF(O^{++}/H^+) = $(O^{++}/H^+)_{RL}$ / $(O^{++}/H^+)_{\rm CEL}$, (e. g. Liu 2006). The ADF(O^{++}/H^+) value is larger than predicted by simple photoionization models for about two thirds of the well observed PNe.

A similar abundance difference for C^{++}/H^+ has been obtained by Peimbert, Torres-Peimbert, & Luridiana (1995) based mainly on the line intensities compilation by Rola & Stasińska (1994). Peimbert et al. (1995) compared the C^{++}/H^+ abundances derived from the C II λ 4267 recombination line with those derived from the C^{++} $\lambda\lambda$ 1906, 1909 collisionally excited lines. Again about one third of the ADF(C^{++}/H^+) of the well observed PNe might be explained by simple photoionization models but two thirds present values too large to be reproduced by these models.

Zhang et al. (2005) have obtained large T_e([O III]) $- T_e$(He I) differences for 48 PNe that can not be explained by simple photoionization models.

2.2. *Possible sources of temperature variations*

Torres-Peimbert & Peimbert (2003) have discussed several mechanisms as possible sources of temperature variations.

Deposition of mechanical energy: there is ample evidence that the central star can inject energy into the nebula: stellar winds, bipolar flows, multipolar flows, and asymmetrical ejections. That this is the case can be confirmed by the strong X-ray emission in BD+30^o 3639, NGC 40, NGC 2392, NGC 3242, NGC 6543, NGC 7009, and NGC 7027 (Guerrero et al. 2005; Guerrero, Chu, & Gruendl 2006). NGC 6302 and NGC 6537 show evidence of high temperatures as high as $\sim$ 50,000 K indicative of shock heating (Rowlands, Houck, & Herter 1994) NGC 2392, NGC 2371-2, NGC 2818, NGC 6302, and Hu 1-2 have large velocity dispersions associated with large temperature variations (Peimbert et al. 1995). In a sample of 47 PNe the shell expansion velocity increases with age (Medina, Peña, & Stasińska 2006; Richer et al. 2008) found that a substantial fraction of the nebular material presents turbulent motions.

Chemical inhomogeneities: The presence of chemical inhomogeneities within the nebula can introduce substantial temperature inhomogeneities. This case will be discussed in the following section.

Time dependent ionization: A photoionization front passing through a nebula can heat the gas promptly, while there is a time delay in attaining thermal equilibrium. This mechanism might explain the presence of hot external halos in PNe (e.g. Tylenda 2003; Sandin et al. 2006). Conversely a decreasing stellar ionizing flux, can create cold partially ionized outer regions, which might explain the low T_e(Balmer) values derived by Luo & Liu (2003) in the outer regions of NGC 7009.

Density irregularities: Extreme density irregularities exist in most PNe, as can be seen from optical images. These density irregularities are very sensitive to time dependent processes, the regions of higher density being able to attain equilibrium sooner than the lower density ones.

Deposition of magnetic energy: The nebular temperature can be affected by by the presence of magnetic energy. This mechanism is not included in the photoionization models.

Dust heating: Stasińska & Szczerba (2001) analyzed PNe photoionization models with heating by dust grains have. In the case of large density irregularities this effect may play and important role.

Shadowed regions: In the nearby PNe NGC 7293 and NGC 6720, molecular globules are present. It is reasonable to expect other PNe to have globules as well. According to Huggins & Frank (2006) the shadow by these globules would produce a covering factor of 5%. This effect would produce a significant difference in temperature in the regions directly ionized by the central star, from those ionized by diffuse radiation (Mathis 1976).

2.3. *Additional evidence*

The comparison of stellar abundances of NGC 6543 based on a non-LTE model with those derived from recombination of the gaseous nebula show excellent agreement, while those derived from collisionally excited lines are a factor of 2 to 4 lower than the stellar ones (Georgiev et al. 2008).

For galactic H II regions the carbon values determined for the ISM of the solar vicinity based on recombination lines of C II and O II (Esteban et al. 2005) are in excellent agreement with the Asplund, Grevesse, & Sauval (2005) solar values. Taking into account the increase in these quantities in the ISM since the time the Sun was formed; the increases in C/H and O/H are those predicted by Galactic chemical evolution models by Carigi et el. (2005).

Liu et al. (2001), presented a strong correlation between the ADF(O^{++}/H^{+}) and T_e([O III]) $-$ T_e(Balmer) and mention that this correlation strongly supports the idea that temperature variations are real. Similarly, from the ADF(C^{++}/H^{+}) values by Peimbert et al. (1995) and others in the literature and the T_e(Balmer) values by Zhang et al. (2004), a strong correlation between the ADF(C^{++}) and T_e([O III]) $-$ T_e(Balmer) is found, result that also supports the presence of temperature variations.

3. CHEMICALLY INHOMOGENEOUS CASE

On the other hand, to explain the ADF values a two component system has been proposed: the hot low density matter that produces the collisionally excited lines and small packets of dense low density matter very rich in heavy elements. In this scheme heavy element optical recombination lines and collisionally excited lines arise from largely unrelated parcels of gas, in accordance with dual-abundance photoionization models (Péquignot et al. 2002). The argument is that this hydrogen-deficient, highly ionized plasma may well (i) have been recently ejected from the nucleus in the form of clumped gas, or (ii) be part of circumstellar material very close to the star in the form of a disc-torus structure (based on the spatial correlation of the diagnostics with the position of the central star), or equally that (iii) it originates from high-excitation gas presently being photoevaporated from milliparsec scale neutral condensations embedded in the nebulae at the limit of our spatial resolution. In case (i), the physical origin of the enhanced heavy-element ORL emission could be an ensemble of hydrogen-poor clumps analogous to the H-poor knots observed in the class of nebulae, such as Abell 30 or Abell 58 (e.g. Borkowski et al. 1993; Guerrero & Manchado 1996). In case (ii), the hydrogen-deficient gas could arise from circumstellar structures such as those discovered by VLT interferometric observations in association with C-stars, post-asymptotic giant branch stars and PNe (Deroo et al. 2007a,b; Chesneau et al. 2007). In case (iii), the H-poor plasma could originate in evaporating dusty "cometary knots" analogous to those in the Helix nebula (NGC 7293; e.g. Meaburn et al. 1992) immersed in high ionization nebular zones both near and farther out from the stars. Although Meixner et al. (2005) note that the Helix globules are rich in molecular hydrogen, this hypothesis would require a mechanism for the efficient removal of hydrogen and/or the chemical differentiation of the evaporated gas for the spectroscopic signature of H-poor plasma to be observed. Also, in the Helix nebula at least, there is no evidence of globules inside the high ionization He II zone or of He II emission from the observed globules, and these features are mostly associated with emission from lower ionization species (O'Dell et al. 2002; O'Dell, Henney, & Ferland 2007).

The support of the two-abundance nebular model is that it provides an explanation for the observed T_e(Balmer) $-$ T_e(He I) differences, but it does not provide an explanation for the temperature variations responsible for the difference between T_e([O III]) and T_e(Balmer). The main evidence for the two abundance nebular model has been provided by Zhang et al. (2005) who found an average difference of $T_e(\text{Balmer}) - T_e(\text{He I}) = 4000$ K from the ratio of the λ 6678 to λ 7281 recombination lines of He I in 48 PNe. The large discrepancies measured between abundances and temperatures obtained from recombination lines and continua versus those obtained from the bright forbidden lines remain a major problem (e.g. Liu et al. 2000, 2004; Tsamis et al. 2003, 2004; Wesson, Liu, & Barlow 2003).

Indeed chemically inhomogeneous nebulae can be produced by H-poor stars that eject material into H-rich nebulae. That is the case of A30 and A78 (Jacoby 1979; Hazard et al. 1980; Jacoby & Ford 1983; Manchado, Pottasch, & Mampaso 1988; Wesson, Liu, & Barlow 2003). This type of situation might occur in those cases where the central star is H-poor. According to Gorny & Tylenda (2000) about 10% of the central stars of PNe are H-poor; while, from the results of the Sloan project, Kleinman et al. (2004) find for DA and DB white dwarfs 91% are non magnetic DAs and 9% are non magnetic DBs. From these numbers, Peimbert & Peimbert (2008) conclude that about 10% of Galactic PNe have a H-poor central star, and might show He, C, and O rich inclusions in their expanding shells and thus it is unlikely for PNe with H-rich central stars to have significant amounts H-poor material in their associated nebulae.

According to Liu et al. (2006) for the majority of more than 100 PNe surveyed thus far by long-slit spectroscopy, abundances of the elements carbon, oxygen, nitrogen and neon derived from their optical recombination lines are higher than those derived from the classic collisionally excited lines by factors of 2 to 3. However for about 5 to 10 per cent of the cases, the discrepancies are in the 4 to 70 range, with Hf 2-2 being the most extreme case (Liu et al. 2006).

Tsamis et al. (2008) have carried out an integral field spectroscopic study of NGC 6153 where they find that in the central regions of this object, there is a weak correlation among some of the emission line intensity and He ionization fraction with the extinction constant. They claim that this result yields new observational evidence in support of predictions of the dual-abundance PN models of Péquignot et al. (2002, 2003)

In the cases of carbon, nitrogen and oxygen, large metal overabundances are correlated with lower plasma temperatures derived from optical recombination lines and continua than from forbidden lines.

4. OBSERVATIONS

For our part we have tried to ascertain the kinematical differences among the optical recombination lines of the heavy elements and those of the collisionally excited lines of the same elements. This can be performed for the oxygen lines.

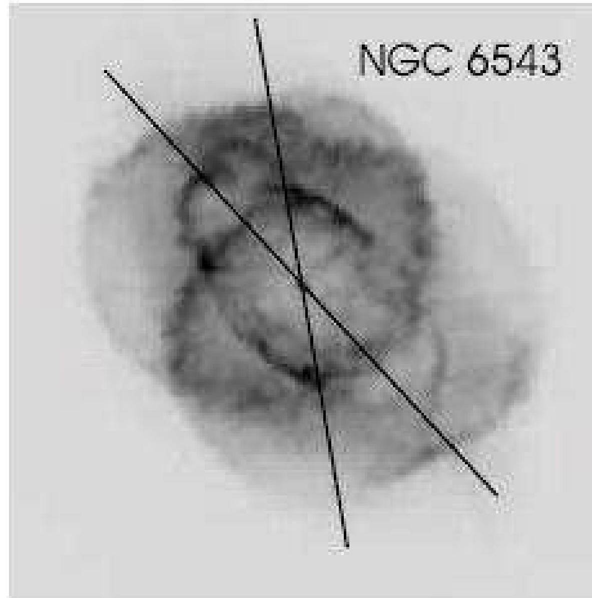

Fig. 1. HST image of NGC 6543 (filter F656N) The slit positions of our observations are superposed. The slit length is shown to scale. North is up and east is left in all of the images. Position angle is 11° for slit *a* and 43° for slit *b*.

For this purpose we obtained long slit echelle spectra at the Observatorio Astronomico Nacional in San Pedro Martir, Baja California with the 2.1 m telescope and the REOSC echelle spectrograph (R $\sim$ 18,000 at 5,000 Å and a 1024×1024 Tektronix detector that yields a spectral resolution of 10.6 km sec^{-1} and a spatial resolution of 0.99″ per pixel. The 3600 to 6850 Å range was covered in 29 orders.

We observed two slit positions in NGC 6543. In Figure 1 we show the positions of the slit. The PA for slit *a* s of 11° and for slit *b* of 43°. These same positions were observed and reported for studies of iron depletion in hot bubbles by Georgiev et al. (2006).

From these observations we present the position-velocity diagrams along the slit for lines of different ions in order of increasing ionization potentials in Figure 2 and Figure 3. In both cases we present the diagrams for [O I] 6300, [S II] 4069, H I 4340, Si II 5041, [S III] 6311, He I 4471, [Cl III] 5517, C II 4267, O II 4649,[O III] 4346, [Ar IV] 4740, Ne III 3869, [K IV] 6102, N III 4634, and C III 4650 lines.

In Figure 4 and Figure 5 we present for both slits the oxygen lines for [O II] 4363, O II 4649, O II 4662 as well as the ratios 4649/4363, 4662/4363 and 4649/4662. The ratios have been normalized and do not show any systematic differences. For each of these slit positions the corresponding minimum,

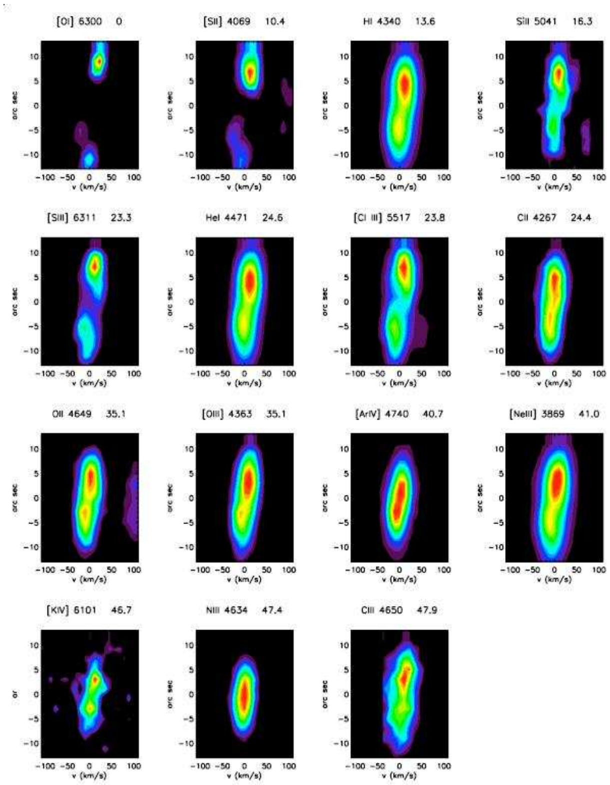

Fig. 2. Position velocity diagram of emission lines for slit position *a* in increasing order of excitation potential for the [O I] 6300, [S II] 4069, H I 4340, Si II 5041, [S III] 6311, He I 4471, [Cl III] 5517, C II 4267, O II 4649, [O III] 4346, [Ar IV] 4740, Ne III 3869, [K IV] 6102, N III 4634, and C III 4650 lines. The line identification and excitation potential are given above each diagram.

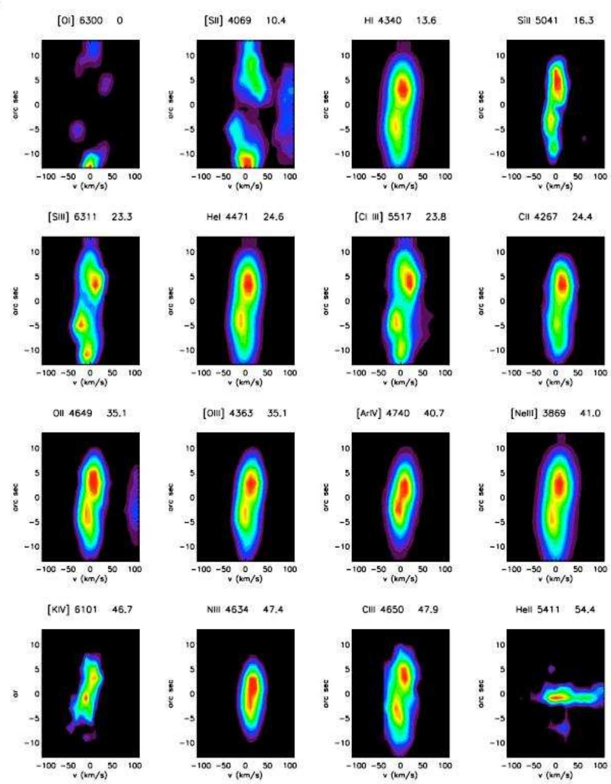

Fig. 3. Position velocity diagram of emission lines for slit position *b* in increasing order of excitation potential for the [O I] 6300, [S II] 4069, H I 4340, Si II 5041, [S III] 6311, He I 4471, [Cl III] 5517, C II 4267, O II 4649, [O III] 4346, [Ar IV] 4740, Ne III 3869, [K IV] 6102, N III 4634, and C III 4650 lines.The line identification and excitation potential are given above each diagram.

TABLE 1

VALUES OF THE OXYGEN LINE RATIOS[a]

Ratio[b]	NGC 6543-A			NGC 6543-B		
	min	max	rms	min	max	rms
4649/4363	0.71	1.16	70	0.77	1.17	78
4662/4363	0.70	1.30	92	0.65	1.55	117
4662/4649	0.72	1.54	98	0.71	1.46	90

[a]Line intensities have been normalized.

[b]rms values in units of 10^{-3}.

maximum and rms values of the ratios are given in Table 1

5. DISCUSSION

From our observations, within the observational uncertainties, we do not find evidence for different kinematical behavior of the optical recombination line emission and the collisionally excited line emission of oxygen. Therefore, in case there are high density knots embedded in the overall gaseous medium, they appear to have the same kinematic behavior and concentration as the low density normal abundance gaseous medium.

We consider that this type of studies can further advance the clarification of the situation of the chemical abundance of the gaseous nebulae.

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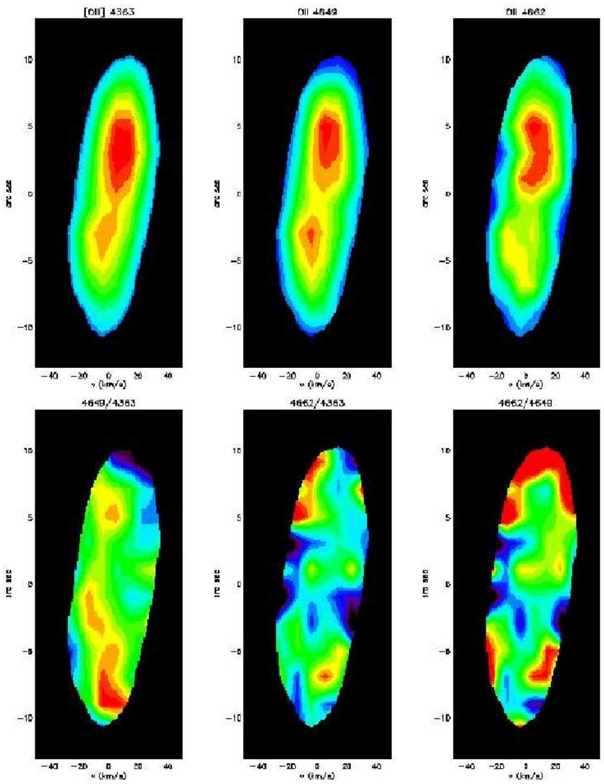

Fig. 4. In the upper panels are the position velocity relations for the oxygen lines for slit *a* [O I] 6300,O II 4649, and O II 4662. In the bottom panels are the 4649/4363, 4662/4363 and 4662/4649 ratios. The diagrams have been normalized.

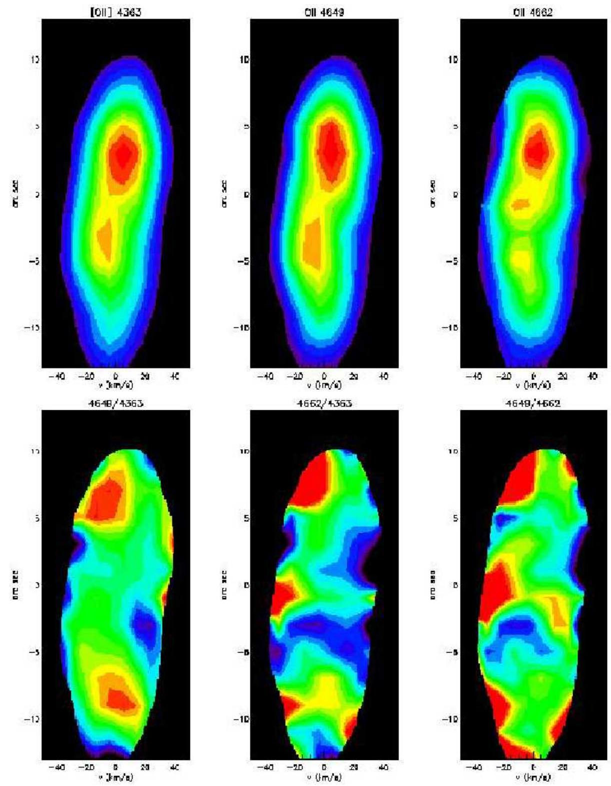

Fig. 5. In the upper panels are the position velocity relations for the oxygen lines for slit *b* [O I] 6300,O II 4649, and O II 4662. In the bottom panels are the 4649/4363, 4662/4363 and 4662/4649 ratios. The diagrams have been normalized.

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