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Letter to the Editor

NICS–TNG infrared spectroscopy of NGC 1068: The first extragalactic measurement of [P II] and a new tool to constrain the origin of [Fe II] line emission in galaxies

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Abstract. We report 0.9–1.4 μm spectroscopic observations of NGC 1068 collected during the commissioning phase of the near infrared camera spectrometer (NICS) of the Telescopio Nazionale Galileo (TNG). These yielded the first extragalactic measurement of [P II] (1.188 μm) line emission. In the central $0.75'' \times 2''$ the [Fe II]/[P II] line-intensity ratio is close to unity, similar to that measured in the Orion bar and a factor of $\lesssim$20 smaller than in supernova remnants. This indicates that most of iron is locked into grains and, therefore, argues against shock excitation being the primary origin of [Fe II] line emission in the central regions of NGC 1068. We propose the [Fe II]/[P II] ratio as a simple and effective tool to study and perhaps resolve the long debated questions related to the origin of [Fe II] line emission and, more generally, to constrain the role of shock excitation in active galaxies.

Key words. line: formation – line: identification – galaxies: active – galaxies: individual: NGC 1068 – galaxies: seyfert – infrared: galaxies

1. Introduction

Since the first infrared spectroscopic observations of galaxies and supernova remnants in the 80's, the emission lines of [Fe II] have become a popular and debated issue (Moorwood & Oliva 1988; Forbes & Ward 1993; Simpson et al. 1996; Veilleux et al. 1997; Alonso–Herrero et al. 1997; Mouri et al. 2000).

From the observational point of view, [Fe II] is weak in HII regions and planetary nebulae while extremely strong in shock–excited filaments of supernova remnants. Since relatively bright [Fe II] emission is commonly found in the IR spectra of normal and active galaxies, many authors have considered the possibility of using this line as shock tracer and, even, to count the number of supernova remnants (e.g. Colina 1993; Vanzi & Rieke 1997; Engelbracht et al. 1998).

From the theoretical point of view, a low density region with normal abundances can become a strong source of [Fe II] only if the following conditions are satisfied.

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i) Most of iron must be in the gas phase, i.e. dust grains must have been destroyed;

ii) The gas electron temperature must be large enough to collisionally excite the upper levels of the lines, in practice $T_{\rm e} \gtrsim 5000$ K;

iii) Most of iron must be singly ionized, i.e. Fe^+/Fe must be close to unity.

Given the low ionization potential of Fe^+ and the high efficiency of the $Fe^{++} + H^o$ charge–exchange recombination reactions, the latter two conditions are equivalent to saying that bright [Fe II] lines can only be formed in regions where hydrogen is partly ionized (e.g. Oliva et al. 1989).

The most efficient mechanisms for creating extended regions of hot, partially ionized gas are shocks and photoionization by soft X–rays. In both cases the volume emission measure of the partially ionized region could easily exceed that of the fully ionized gas. The only important difference between the two mechanisms is that photoionization is unable to destroy the toughest iron–based grains which are otherwise easily sputtered by shock fronts.

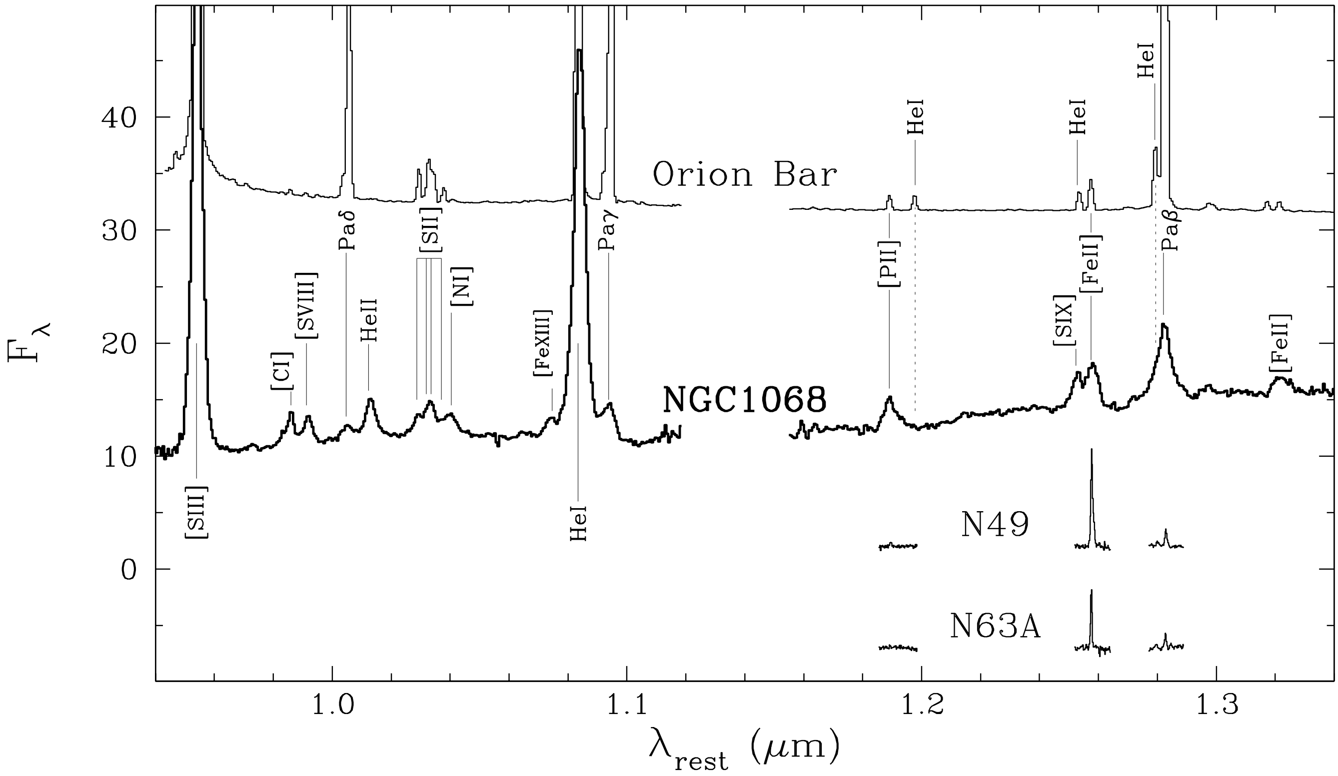

Fig. 1. NICS–TNG spectrum of the Seyfert galaxy NGC 1068 compared with spectra of template objects from the literature (see text Sect. 2). The break at $\simeq$1.1 μm corresponds to the region of bad atmospheric transmission. The flux scales and zero levels have been adjusted to facilitate the direct comparison between the spectra

In practice, therefore, a purely photoionized region emitting [Fe II] can be easily recognized by measuring the abundance of Fe^+ relative to any non-refractory species which forms in the same partially ionized region. Finding a very low iron abundance would unequivocally imply that the gas has not been significantly processed by shocks.

This could be in principle obtained by comparing the infrared [Fe II] and optical [O I] lines but, in practice, the large difference in critical densities, reddening and the problems of comparing data taken with different instruments makes it impossible to obtain a clear–cut conclusion (see e.g. Mouri et al. 1993; Alonso–Herrero et al. 1997; Larkin et al. 1998). A much more reliable determination of the iron relative abundance should be derived from lines close in wavelengths and with similar critical densities such as the [P II] and [Fe II] lines which are discussed in this Letter.

2. Observations and results

The data were collected at the Telescopio Nazionale Galileo (TNG) in November 2000 during the commissioning phase of NICS, the near infrared camera and spectrometer expressly designed and built for this telescope. This instrument is a FOSC–type cryogenic focal reducer equipped with two interchangeable cameras feeding a Rockwell Hawaii 1024^2 array. The camera used for the spectroscopic observations has a projected scale of $0.25''$/pixel (Oliva & Gennari 1995; Baffa et al. 2000). The spectroscopic modes are achieved by means of a series of glass–resin grisms which can be inserted in the 22 mm collimated beam (Vitali et al. 1997). The spectrum of NGC 1068 was collected through a slit of $0.75''$(=3 pixels) width and using the IJ grism which yields a 0.89–1.46 μm spectrum with a dispersion of 5.7 Å/pix. The slit was oriented N–S (i.e. at PA = 0°) and centered on the 1 μm continuum peak. The acquisition consisted of a series of four 5–minute exposures with the object set at different positions along the slit followed by halogen flats. The atmospheric spectral response and the instrumental efficiency were determined using spectra of the O6.5 V star HD 42088 whose intrinsic spectrum was approximated by $F_\lambda = 1.7\ 10^{-9}\ (\lambda/1.25)^{-3.7}$ erg cm^{-2} s^{-1} μm^{-1}.

The spectrum of the central $0.75'' \times 2''$ region is displayed in Fig. 1 where we also show, for comparison, spectra of the Orion Bar (Walmsley et al. 2000) and unpublished spectra of supernova remnants collected in 1992 using IRSPEC at the ESO-NTT telescope. The relative line fluxes are summarized in Table 1. Evident is the difference between the very large [Fe II]/[P II] ratio measured in SNR's and the much smaller values found in the Orion Bar and in NGC 1068.

In principle, the emission feature peaking at 1.188 μm could be contaminated by [Ni II] 1.191 μm. However, this line was measured in the Crab nebula at a level of only $\lesssim$15% of [Fe II] (Rudy et al. 1994) and was not detected in the supernova remnants listed in Table 1. Moreover, [Ni II]

Table 1. Line fluxes in NGC 1068 and template objects

Line (μm)	Relative fluxes[(1)]				
	NGC 1068	Orion	RCW 103	LMC-N63A	LMC-N49
[SIII] 0.9529	1200	29 000	–	–	–
[CI] 0.985	72	20	–	–	–
[SVIII] 0.9913	55	<10	–	–	–
Paδ 1.005	61:	1400	–	–	–
HeII 1.012	120	<10	–	–	–
[SII] 1.033	170:	400	–	–	–
[NI] 1.040	60:	14	–	–	–
[FeXIII] 1.075	50:	<10	–	–	–
HeI 1.083	1000	6600	31	–	–
Paγ 1.094	110:	2300	<15	–	–
[PII] 1.188	67	50	<8	<6	3
HeI 1.197	<20	48	<8	<6	<6
[SIX] 1.252 + HeI 1.253	72[a]	66[b]	<8	<6	<6
[FeII] 1.257	100	100	100	100	100
HeI 1.279	50:	430	–	<6	<6
Paβ 1.282	230	4300	11	20	15
[FeII] 1.321	33	34	30	–	–
[FeII] intensity[(2)]	≈20[c]	4.4	12	3.0	4.4

(1) Normalized to I([FeII]1.257) = 100. Fluxes for Orion refer to position A of Walmsley et al. (2000), values for the supernova remnants are from Oliva et al. (1990) and from the IRSPEC spectra displayed in Fig. 1. The error on line fluxes in NGC 1068 are tyipically ±10% except for the entries marked with a ":" which are uncertain due to blending.
(2) Intensity of [FeII] 1.257 in units of 10^{-4} erg cm^{-2} s^{-1} sr^{-1}.
a Contribution from HeI 1.253 should be ≃10, based on the observed intensities of the other HeI lines.
b Contribution from [SIX] is negligible.
c The absolute flux calibration is uncertain.

has a critical density of only ≃500 cm^{-3} (Nusbbaumer & Storey 1982), two orders of magnitude lower than the critical density of [Fe II] and much lower than the electron density pertinent to the region of NGC 1068 under consideration here. For these reasons we believe that [Ni II] does not affect significantly the measurement of [P II].

It is also interesting to note that our data confirm the identification of [SIX] by Marconi et al. (1996) and include the first detection of [Fe XIII] in an extragalactic object. The latter identification is also supported by measurements of the higher ionization green line of [Fe XIV] (Kraemer & Crenshaw 2000).

3. Discussion

3.1. [Fe II], [P II] and the Fe/P abundance ratio

The near–IR lines of [P II] and [Fe II] have several interesting similarities. They lie nearby in wavelength, have similar excitation temperatures and critical densities and their parent ions have similar ionization potentials and radiative recombination coefficients. Using the collision strengths of Krueger & Czyzak (1970), Zhang & Pradhan (1995) and the transition probabilities of Mendoza & Zeippen (1982), Nussbaumer & Storey (1988) yields

$$\frac{n(\mathrm{Fe}^+)}{n(\mathrm{P}^+)} \simeq 2 \cdot \frac{I([\mathrm{Fe\,II}]\ 1.257\ \mu\mathrm{m})}{I([\mathrm{P\,II}]\ 1.188\ \mu\mathrm{m})} \tag{1}$$

which is accurate within a factor of 2 for all the temperatures and densities of interest. The only important difference between the two species is that charge exchange recombinations between P^{++} and neutral hydrogen are ≃2 orders of magnitude less efficient than the Fe^{++} + H^o reactions (Kingdon & Ferland 1996). This implies

$$\frac{n(\mathrm{Fe}^+)}{n(\mathrm{P}^+)} \gtrsim \frac{n(\mathrm{Fe})}{n(\mathrm{P})} \tag{2}$$

which combined with Eq. (1) yields

$$\frac{n(\mathrm{Fe})}{n(\mathrm{P})} \lesssim 2 \cdot \frac{I([\mathrm{Fe\,II}]\ 1.257\ \mu\mathrm{m})}{I([\mathrm{P\,II}]\ 1.188\ \mu\mathrm{m})} \tag{3}$$

i.e. the Fe/P abundance ratio is quite well constrained by the [Fe II]/[P II] ratio and, if anything, it is overestimated. Finally, it is interesting to note that, for a solar Fe/P ≃ 100 abundance ratio, one expects [Fe II]/[P II] ≃ 50 i.e. a ratio similar to that measured in supernova remnants.

3.2. Fe/P abundance ratio and dust destruction

Iron is a well known refractory species whose gas phase abundance in the ISM is often found to be down by many orders of magnitudes relative its cosmic value. The only regions where iron is not found to be significantly depleted are those associated with fast (≳100 km s^{-1}) shocks which can effectively destroy the grains by sputtering. In normal photoionized regions the depletion of iron ranges between the factor of ≃0.1 measured in the Orion Bar (Baldwin et al. 1996) to significantly lower values found in planetary nebulae (e.g. Oliva et al. 1996; Perinotto et al. 1999). These differences probably reflect the fact that a variable (though small) fraction of iron is locked into relatively soft grains which can be easily destroyed without the need of fast shocks.

Phosphorus is a non-refractory species whose measured depletion in ionized gas is close to unity. Therefore, the Fe/P relative abundance should give a direct estimate of the iron depletion or, equivalently, of the presence of robust dust in a given region. This is indeed confirmed by the data presented here (Fig. 1 and Table 1) which show variations by more than one order of magnitude between the large, quasi–solar Fe/P ratio found in SNR's and the much smaller values found in the other objects.

3.3. [Fe II]/[P II] and the origin of [Fe II] in galaxies

As already discussed in the introduction, determining the origin of [Fe II] line emission is of crucial importance for any program aiming at using [Fe II] for tracing shock fronts and/or constraining the supernovae rate in galaxies. The results obtained here indicate that the [Fe II]/[P II] ratio could provide a clear–cut answer to this problem. The line ratio is large ($\gtrsim$20) in regions excited by fast shocks while low ($\lesssim$2) in normal photoionized region and in NGC 1068. This indicate that shocks are *not* the dominant source of [Fe II] in the central ≃200 pc of NGC 1068 where, most likely, the lines are produced by photoionization from the active nucleus, as already indicated by detailed photoionization modeling (e.g. Kraemer & Crenshaw 2000). The copious flux of soft X–rays from the AGN creates a very extended partially ionized region which is responsible for the strong emission of low ionization species such as [S II], [O I], [P II] and [Fe II]. However, the latter is relatively weak because most of the iron is locked into dust grains. The relative intensities of the low and higher ionization lines depend on a complex combination of the ionization parameter, density and of the spectral shape of the ionizing radiation. Nevertheless, the ratio between "close relatives" such as [Fe II]/[P II] are little influenced by this and, as discussed in Sect. 3.1, almost solely depend on the Fe/P relative abundance which, in turn, is a direct measurement of iron depletion (Sect. 3.2).

4. Conclusions

Given the above results and considerations, we propose using the ratio between [Fe II] (1.257 μm) and [P II] (1.188 μm) as a general tool for constraining the origin of [Fe II] line emission in galaxies. The diagnostic works as follows

– In objects with low [Fe II]/[P II] ratios shocks do *not* play an important role in the lines excitation;
– Large values of [Fe II]/[P II] ($\gtrsim$20) indicate that the emitting gas has recently passed through a fast shock which sputtered and destroyed most of the dust grains. It is therefore likely that the lines are also produced by shock excitation.

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