2001
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ELEMENT ABUNDANCES AND DISTRIBUTIONS IN THE CRAB NEBULA
Revista Mexicana de Astronomía y Astrofísica, número 010
Universidad Nacional Autónoma de México
Distrito Federal, México
pp. 27-28

RevMexAA (Serie de Conferencias), **10**, 27–29 (2001)

ELEMENT ABUNDANCES AND DISTRIBUTIONS IN THE CRAB NEBULA

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RESUMEN

La Nebulosa del Cangrejo proporciona oportunidades únicas para investigar diversos aspectos de la nucleosíntesis y del enriquecimiento de elementos relativos a la estrella progenitora y a la estrella de neutrones joven. Se pueden combinar datos espectroscópicos e imágenes para conocer la distribución de abundancias. Nuestros conocimientos sobre esta remanente de supernova han aumentado de manera considerable en los últimos años.

ABSTRACT

The Crab Nebula provides unique opportunities for investigating various aspects of element production or enrichment related to the progenitor star and also to the young neutron star. Spectroscopic and imaging data may be combined with photoionization analyses to elucidate abundance distributions. Our understanding of this young supernova remnant has undergone significant advances in recent years.

Key Words: **ISM: ABUNDANCES — ISM: INDIVIDUAL (CRAB NEBULA)— ISM: SUPERNOVA REMNANTS—STARS: NEUTRON STARS**

The Seventh Texas-México Conference on Astrophysics: Flows, Blows and Glows (Austin, Texas, 6-8 April 2000)
Editors: William H. Lee and Silvia Torres-Peimbert

1. INTRODUCTION

Young supernova remnants are excellent laboratories for investigating how stars process and distribute elements, and the Crab Nebula (NGC 1952) has recently begun living up to its promise of providing unique information in this regard. Its young age and location roughly 180 pc from the plane of the Galaxy suggest that the ejecta are not heavily contaminated by swept–up interstellar material. Furthermore, the nebular gas is photoionized by locally generated synchrotron radiation, resulting in a rich emission–line spectrum which can be analyzed using powerful photoionization codes. This is a progress report for abundances and spatial distributions of the elements helium, nitrogen, sulfur, argon, and nickel.

2. DISCUSSION

The existence of a neutron star in the Crab Nebula and the measurement of roughly 2 $M_{\odot}$ of helium in the visible remnant (MacAlpine & Uomoto 1991) are consistent with the progenitor star having initially contained approximately 10 $M_{\odot}$ (Arnett 1975). Then violent flashes prior to core collapse may have caused ejection of the outer envelope (Woosley & Weaver 1986), leaving the observed "helium mantle". An anomalous aspect of this helium–rich gas is the "high–helium torus" (Uomoto & MacAlpine 1987), wherein about 25 percent of the nebula is 95 percent helium by mass fraction, and for which there is still no satisfactory explanation.

For a 10 $M_{\odot}$ star, the helium mantle gas must have formed via the CNO–cycle, so the visible nebula should also be significantly enriched with nitrogen (Wheeler 1978). However, until recently, most existing spectra were not indicative of high nitrogen content, resulting in an apparent dilemma known for nearly two decades as the "nitrogen paradox". Recognizing that nitrogen line emission may be strong at *some* locations in the nebula and that a possible explanation for low nitrogen content at other locations could be further nuclear processing, we (MacAlpine et al. 1996) used systematic long–slit spectroscopic mapping of [N II] $\lambda\lambda$6548, 6583 emission and also photoionization models to show that most of the visible nebular gas does indeed have nitrogen abundances roughly three to seven times higher than solar. On the other hand, measurements for relatively bright regions south of the pulsar are consistent with numerical calculations involving roughly normal nitrogen abundance, but with products of oxygen burning (such as sulfur and argon) enhanced by factors of ten to twenty compared with solar.

Some stellar models for the appropriate precursor star mass range (Woosley & Weaver 1986) suggest that the asymmetrically distributed sulfur–rich material was produced by off–center (in a shell) oxygen burning. Further spectroscopy (Strolger & MacAlpine 1996) strongly supports these conclusions regarding chemical processing. Whereas [S II] emission is *anticorrelated* with [N II], *direct correlation* between [S II] and [Ar III] emission is extremely strong (correlation coefficient of 0.89 for more than 100 locations), as would be expected if the sampled gas is significantly mixed with products of oxygen burning.

Other interesting locations with very strong argon emission are the so–called argoknots (MacAlpine et al. 1994) of line–emitting gas, which are aligned in crude arcs, seven to the north and four to the south, from the pulsar. In each case, the *measured* intensity of [Ar III] λ7136 is unusually strong (as high as four times Hβ). Following discovery of the knots, subsequent spectra showed that they are also exceptionally strong sources of [Ni II] λ7378 emission, especially on the side of each knot oriented toward the pulsar.

It has long been known that certain regions of the Crab Nebula exhibit exceptionally strong nickel line emission (Henry, MacAlpine & Kirshner 1984). In a filamentary arch, toward which the northern argoknots are apparently moving, the measured [Ni II] λ7378 line suggests an abundance enhancement of nickel by a factor of more than 50 compared with solar (MacAlpine et al. 1989), and the nickel to iron ratio appears to be high throughout the nebular gas. Of course, this must be a stable, neutron–rich nickel isotope. But why is it enhanced in the Crab Nebula, and why is it particularly strong in certain regions? Among other explanations, possibilities include production of stable nickel following photodisintegration of prior s–processed heavy nuclei during the oxygen burning episode (Thielemann & Arnett 1985) and also expulsion of stable nickel from the surface of the energetic neutron star (Ruderman & Sutherland 1975). To explore these ideas, the measured [Ni II] λ7378 and [Ar III] λ7136 lines were examined for more than 200 points distributed over the nebula. For those locations with enhanced products of oxygen burning, a strong nickel/argon correlation was seen, apparently supporting the first hypothesis above. In addition, there is another *distinct* and significant correlation involving the strongest nickel lines, possibly supporting the latter hypothesis. The idea that these heavy nuclei may be coming from the surface of the neutron star is particularly intriguing and may also be consistent with other evidence. Both optical polarization mapping (Michel et al. 1991) and the original argoknot discovery images (MacAlpine et al. 1994) suggest a relativistic wind to the north and south from the pulsar, and the nickel line intensities in those directions, particularly on the sides of the knots toward the pulsar, are exceptionally strong.

In summary, assuming the visible gas in the Crab Nebula represents the helium mantle from a 10 $M_\odot$ progenitor star, the overall amount of helium seems reasonable; but the extreme concentration in the high–helium torus remains a mystery. In addition, measured nitrogen abundances for most of the gas now appear consistent with the rest of our understanding for this remnant, while the existence of regions where products of oxygen burning dominate the abundances may also be expected. Finally, high nickel–line emission and its distribution may suggest the intriguing prospect of direct enrichment from the neutron star.

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