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THE 5° DIAMETER IONIZED HALO OF THE PLANETARY NEBULA ABELL 36

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ABSTRACT

We have observed an ionized halo surrounding the planetary nebula Abell 36. It is barrel-shaped, with dimensions $4^\circ \times 5^\circ$, which is $17 \text{ pc} \times 21 \text{ pc}$ at a distance of 240 pc. With an average $\text{H}\alpha$ surface brightness of 0.8 ± 0.2 rayleighs, the halo's total $\text{H}\alpha$ flux, $8.3 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}$, exceeds that of the previously known inner part of the nebula by a factor of 30. The ionized mass of the halo is $48\sqrt{\epsilon} M_\odot$, where ϵ is the filling factor of the ionized gas. Velocity-resolved $\text{H}\alpha$ spectra indicate that the halo is ambient interstellar matter and not matter ejected from the planetary nebula. The edges of the halo are evident in both $100 \mu\text{m}$ emission and red optical continuum.

Key words: ISM: general — planetary nebulae: individual (A36)

1. INTRODUCTION

The inner part of the nebula of Abell 36 (A36) looks like the better-known, helically shaped “cat’s-eye” nebula NGC 6543, with two pairs of bipolar lobes (Hua & Kwok 1999). We detect a very large (5°), faint halo of ionized material surrounding A36 in our $\text{H}\alpha$ observations. Hereafter we will refer to the previously known inner part as the “core” and the newly discovered outer part as the “halo.” Evidence that the core of A36 is optically thin to ionizing radiation is (1) the relative brightnesses of its hydrogen and helium emission lines (Kaler, Shaw, & Kwitter 1990), and (2) its helical shape (Hua & Nguyen-Trong 1983). Apparently, the ionizing radiation that leaks out of A36’s core ionizes the surrounding, ambient interstellar medium (ISM), thereby creating the halo that we observe in $\text{H}\alpha$ with a surface brightness of 0.8 ± 0.2 rayleighs. One rayleigh (R) is equivalent to $5.7 \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}$ at $\text{H}\alpha$.

The core of A36 was identified by Abell (1966) among many other planetary nebulae (PNe) on the Palomar Observatory Sky Survey plates. Abell measured the nebula to be $478'' \times 281''$, with a peak surface brightness of $22.8 \text{ mag arcsec}^{-2}$ on the red plate. High-sensitivity work by Hua & Nguyen-Trong (1983) compared the structure of A36 visible in $\text{H}\alpha$ to that of NGC 6543 and suggested that the helical shape with extended filaments could result in geometrical nonuniformities in optical depth.

The trigonometric parallax of the central star of A36, FB 138, has been measured by the *Hipparcos* satellite to be $4.12 \pm 2.47 \text{ mas}$ (Acker et al. 1998). Based on the parallax and its error, Acker et al. (1998) report a range of distance from 150 to 600 pc and adopt a value of 240 pc. For this paper, we also adopt 240 pc as the distance to A36, although the 1.7σ measurement of the parallax implies that

the distance could be much larger than 240 pc. The parallax is of poor signal-to-noise ratio partly because of A36’s large distance and also because the $V = 11.5$ magnitude star is near the limit of detectability for *Hipparcos*, $V = 12.4$ (Perryman et al. 1997). Other distance estimates are 0.375 and 0.4 kpc (Cahn, Kaler, & Stanghellini 1992 and Abell 1966, respectively). If A36 is 240 pc away, then its position $[(l, b) = (318^\circ, +41^\circ)]$ places it 157 pc above the Galactic plane.

A36’s core dimensions of $481'' \times 281''$, or $0.56 \text{ pc} \times 0.33 \text{ pc}$, correspond to dynamical ages of 8000 yr and 4700 yr, respectively, assuming a constant, characteristic expansion velocity of $+34 \text{ km s}^{-1}$ (Bohuski & Smith 1974). Kaler et al. (1990) place a lower limit on the central star effective temperature of $T_{\text{eff}} > 73,000 \text{ K}$. Méndez et al. (1981) measure a surface gravity of $\log g = 5.2 \pm 0.5$.

2. OBSERVATIONS AND RESULTS

The halo of A36 was discovered on images from a robotic $\text{H}\alpha$ survey of the southern celestial hemisphere. That survey is described by Gaustad et al. (1999) and McCullough et al. (1999). The camera’s 52 mm focal length, f/1.6 lens yields a scale at the focal plane of 0.8 pixel^{-1} and a field of view of $13^\circ \times 13^\circ$. The CCD images are taken alternately through a 3 nm wide filter that passes $\text{H}\alpha$ light and a second interference filter designed to exclude $\text{H}\alpha$ light and to measure continuum in two 6 nm bandpasses on each side of $\text{H}\alpha$. The continuum image is then subtracted from the $\text{H}\alpha$ image, with appropriate scaling. Because the CCD response is non-linear at high intensity and because some stars have strong $\text{H}\alpha$ emission or absorption lines, the continuum subtraction is imperfect and leaves residuals around the brighter stars. Spatial filtering eliminates most of the stars’ residuals, at the cost of reducing the angular resolution to $4'$. Each $13^\circ \times 13^\circ$ image results from the superposition of five $\text{H}\alpha$ images and six continuum images. The images are dithered on the sky and combined with median filtering to eliminate optical ghosts of the brightest stars and transient phenomena such

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as satellites. The combined exposure time of each image is 100 minutes through the $H\alpha$ filter and 30 minutes through the continuum filter. In regions that appear to be devoid of genuine structure, the rms intensity variation of the spatially filtered images is 0.25 R. Figure 1 shows the core and the 5° diameter halo of A36 as a mosaic of sections of a few images from the survey.

We measure an $H\alpha$ flux from A36's core (i.e., within a radius of 2.4) of 2.8×10^{-11} ergs cm^{-2} s^{-1} , which is 35% less than the 4.3×10^{-11} ergs cm^{-2} s^{-1} measured by Kaler et al. (1990), and 40% more than the 2.0×10^{-11} ergs cm^{-2} s^{-1} measured by Hua & Kwok (1999).

The mean $H\alpha$ surface brightness of the halo is 0.8 ± 0.2 R, averaged over a 3.6×5.0 ellipse. The uncertainty (0.2 R) is dominated by the difficulty in determining the $H\alpha$ brightness of the surrounding ISM in our images and the Wisconsin $H\alpha$ Mapper (WHAM; see Haffner et al. 2001) spectra. For the $\sim 5^\circ$ diameter halo, the $H\alpha$ flux is 8.3×10^{-10} ergs cm^{-2} s^{-1} , which is 30 times that of A36's core.

It would be surprising if any previous study of PNe had detected the halo of A36, because its angular size is much

larger than typical CCD-telescope combinations permit, and it is fainter than the 0.3×0.4 halo around NGC 3242, which is the one of the faintest PN halos detected on photographic emulsions (Bond 1981). For comparison, Balick et al. (1992) discovered many PN halos with angular diameters not larger than 0.25 and surface brightnesses of 0.4 to 40 R; those halos are thought to be matter ejected by the progenitor star and not interstellar matter, as we will show A36's halo to be. Although surface brightness is conserved over distance (in Euclidean space), the faintest structures detected around PNe in nearby, external galaxies will tend to be brighter than those detected in our own Galaxy; because those nearer the Earth are larger in angular size, they permit integrating over more solid angle and thus averaging down of the noise in an image. For instance, one of the most sensitive $H\alpha$ images of an external galaxy to date is a 5 hr exposure of M33 taken with a Schmidt camera fitted with a CCD. Its scale is $2''$ pixel^{-1} and its surface brightness limit is ~ 2 R (Greenawalt 1998; Walterbos 1998). If A36 were in M33, i.e., 840 kpc away, the PN's halo would be resolved only partially, 2 pixels across, and it

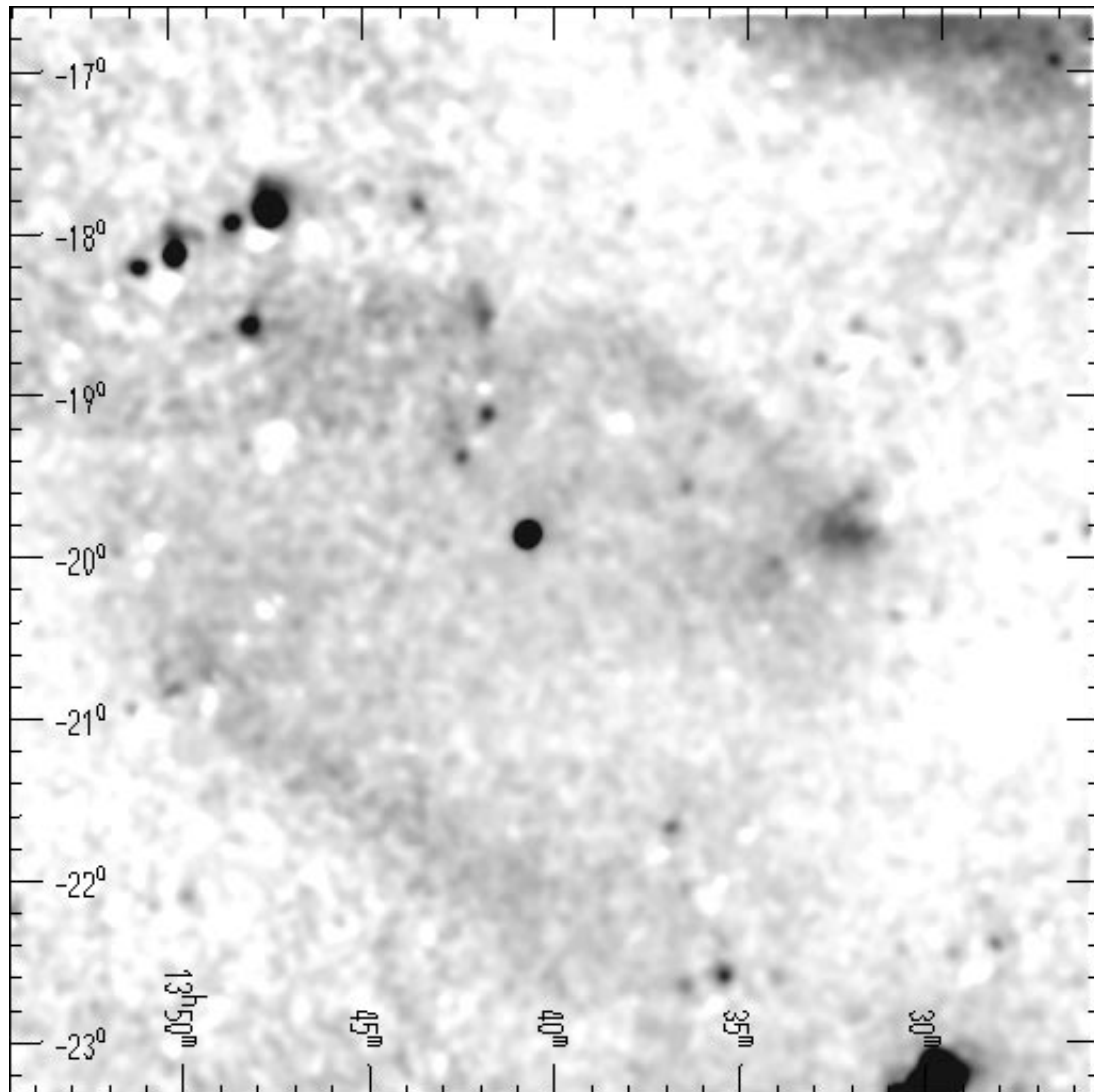


FIG. 1.—Continuum-subtracted $H\alpha$ image of the planetary nebula Abell 36 (black spot at center), showing its 5° ionized halo. Also visible in the upper right corner is the southernmost part of the nebula associated with the B1 III star Spica. Faint discontinuities may result from mosaicking three images: (a) north of $-21^\circ 25'$; (b), south of $-19^\circ 25'$; and (c), west of $13^{\text{h}} 42^{\text{m}} 20^{\text{s}}$ (J2000.0).

would be too faint to detect on that $H\alpha$ image by more than a factor of 2.

When the Magellanic Cloud Emission Line Survey (MCELS; see Smith et al. 1998) is completed, it will be the most comprehensive emission line survey of the Large Magellanic Cloud to date. It uses equipment similar to that used by Greenawalt and Walterbos for M33. The MCELS sensitivity limit is estimated to be 5 R (Smith et al. 1998). If A36 were in the LMC, i.e., 50 kpc away, A36's halo would subtend 1/4, or ~ 40 pixels in the MCELS. By digitally inserting A36's halo (scaled appropriately) into MCELS $H\alpha$ images, we have determined that it would be too faint to detect in those images.

The spectra in Figures 2 and 3 are from the WHAM survey (Haffner et al. 2001). The WHAM survey consists of velocity-resolved $H\alpha$ spectra from a 1° diameter beam Fabry-Pérot spectrometer.

Comparison of spectra of A36's core with those of its halo indicates that the halo is ambient interstellar matter and not circumstellar in origin. If the halo's gas is simply ambient gas photoionized by the central star, we would expect its $H\alpha$ spectrum to resemble the spectrum of other gas in that region of sky. The halo's spectrum should be a brighter copy of the typical spectrum, with similar center wavelength and width. On the other hand, if the halo's gas is truly circumstellar in origin, its spectrum might be expected to peak at the central velocity of the nebula's core and to show some evidence of expansion (such as extra width or a double peak). The core's $[\text{O III}]$ spectrum peaks at $V_{\text{LSR}} = 37.8 \text{ km s}^{-1}$ and has a width separating its double peaks, $\Delta V = 69 \text{ km s}^{-1}$ (Bohuski & Smith 1974). The halo's $H\alpha$ spectrum peaks at $V_{\text{LSR}} = -12 \text{ km s}^{-1}$ and has a width $\text{FWHM} = 32 \text{ km s}^{-1}$ (see Fig. 2). The difference between the central velocities indicates that the halo is not moving with the core. The halo's central velocity and its width are

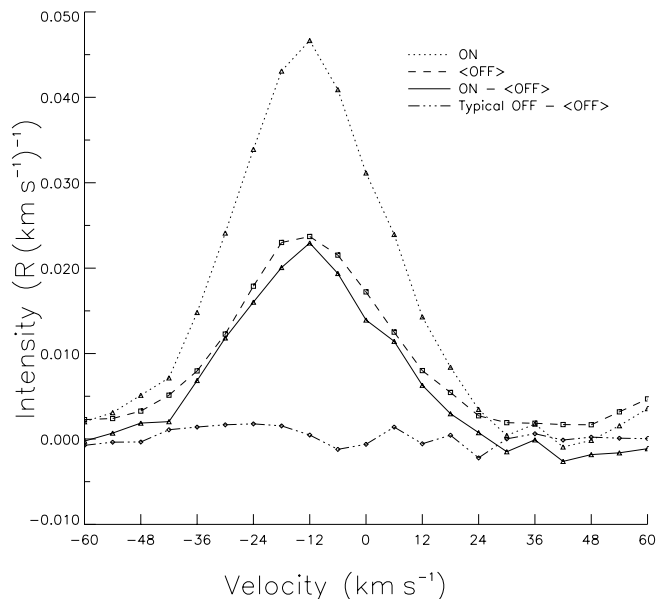


FIG. 2.—Sample WHAM velocity spectra (M. Haffner & R. J. Reynolds 2000, private communication). “ON” is inside the halo ($l = 320^\circ$, $b = 40^\circ$); “<OFF>” is the mean of the area immediately surrounding the halo; “typical OFF” is outside the halo ($l = 314^\circ$, $b = 38^\circ$). A Gaussian fit to the background-subtracted ON location (i.e., ON - <OFF>) has a peak amplitude of $0.022 \text{ R km}^{-1} \text{ s}^{-1}$ at a velocity of -12.6 km s^{-1} relative to the LSR and an FWHM of 30.1 km s^{-1} . The velocity-integrated $H\alpha$ surface brightness of the ON location is 0.70 R above the background level.

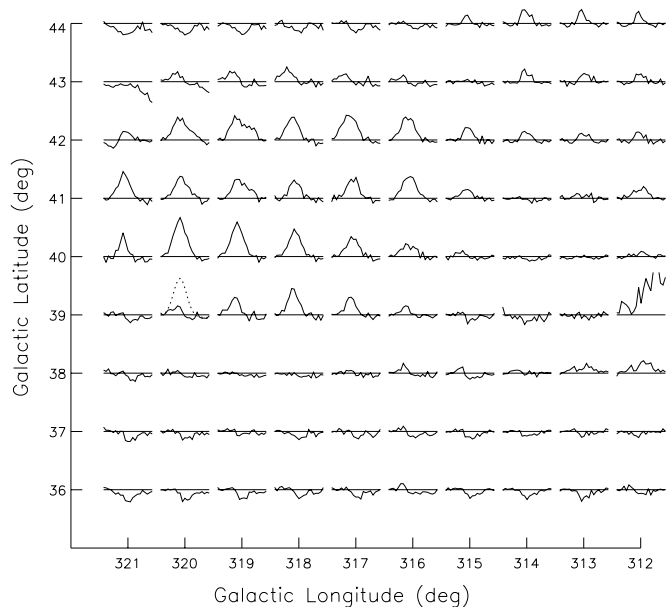


FIG. 3.—WHAM spectra for a $10^\circ \times 9^\circ$ area that includes the halo of Abell 36. The halo is spanned by Galactic longitudes 321° – 316° and Galactic latitudes 39° – 42° . A mean background spectrum has been subtracted from each individual spectrum. The horizontal scale for each spectrum ranges from -60 km s^{-1} to 60 km s^{-1} . To show the intensity and velocity scales, a Gaussian is superposed at $l = 320^\circ$, $b = 39^\circ$; it is a fit to the spectra at $l = 320^\circ$, $b = 40^\circ$, and it has a peak amplitude of $0.022 \text{ R km}^{-1} \text{ s}^{-1}$, a center of -12.6 km s^{-1} with respect to the LSR, and an FWHM of 30.1 km s^{-1} .

nearly identical to those of the $H\alpha$ emission for adjacent regions of sky (see Fig. 2). Based on the spectra, we conclude that the gaseous halo was never part of the central star but instead is a sphere of interstellar gas that has been ionized by the radiation that has leaked out of the core.

The edges of A36's halo, especially along its southern border, are also visible in $100 \mu\text{m}$ emission detected by *IRAS* and in red continuum on our “offband” survey images and on the National Geographic Society/Palomar Observatory Sky Survey. The red continuum is well correlated with the $100 \mu\text{m}$ emission, so we believe it is related to the extended red emission associated with dust (see, e.g., Furton & Witt 1992 and Szomoru & Guhathakurta 1998).

3. DISCUSSION

Evidently, ionizing photons are leaking out of the core and escaping into the interstellar medium. That $\sim 97\%$ of the ionizing photons from A36's central star escape the core to be detected in this 5° diameter halo may have implications for the structure of PNe, the ionization of the diffuse ISM and the Galactic halo, and the Zanstra temperatures of the central stars of PNe.

The total ionized nebular mass of a spherical PN is

$$M_i = 0.041 \epsilon^{1/2} \theta^{3/2} D^{5/2} F_0(H\alpha)^{1/2} M_\odot \quad (1)$$

(Boffi & Stanghellini 1994; Hua & Kwok 1999), and the volume density of electrons n_e (in cm^{-3}) is determined by

$$n_e = \frac{M_i[M_\odot]}{(4\pi/3)(\theta D)^3 \epsilon \mu}, \quad (2)$$

where ϵ is the filling factor of ionized gas, θ is the angular radius in arcminutes, D is the distance to the nebula in kpc, $F_0(H\alpha)$ is the total nebular $H\alpha$ flux, corrected for extinction,

in units of 10^{-12} ergs s^{-1} cm^{-2} , and μ is a constant of proportionality that converts units and accounts for the ionized gas's mean mass per free electron. With common assumptions for the effects of helium (see, e.g., Boffi & Stanghellini 1994), $\mu = 0.74 \times 10^{-3}$. For a distance of 0.24 kpc, and with negligible extinction, the ionized mass for A36's core is $0.032\sqrt{\epsilon}M_{\odot}$ and for its halo is $48\sqrt{\epsilon}M_{\odot}$. The implied electron densities for the core and halo are $33\sqrt{1/\epsilon}$ cm^{-3} and $0.6\sqrt{1/\epsilon}$ cm^{-3} , respectively.

The progenitor stars of PNe have masses between 0.8 and $8 M_{\odot}$ (Iben & Renzini 1983), whereas white dwarfs are less than $\sim 1 M_{\odot}$, so in many cases a large fraction of the progenitor's mass is expelled to form the PN. This implies that a significant amount of ejected mass cannot be accounted for by the ionized cores of many PNe (Buckley & Schneider 1995). In equation (1), the quantities θ and $F_0(H\alpha)$ are observed and are reliable. As noted in § 1, the distance may be significantly larger than the 0.240 kpc assigned. If A36 is 1 kpc away, for instance, then $M_i(\text{core}) = 1.1\sqrt{\epsilon}M_{\odot}$, which reduces the problem of the unseen mass. However, at an assumed distance for A36 of 1 kpc, the electron density of its halo $n_e(\text{halo}) = 0.3\sqrt{1/\epsilon}$ cm^{-3} , whereas the ambient volume density predicted for $Z = 0.65$ kpc by models of the vertical distribution of H I and H II (Kulkarni & Heiles 1987) is $n(\text{ISM}) = 0.027$ cm^{-3} . In other words, to account for the "missing mass" of A36's progenitor, if there is any, it is convenient to suppose that A36 is more than 240 pc away, but if it is too far away the density of the newfound halo becomes implausibly large for that height above the Galactic plane. Another possibility is that the "missing mass" is in the form of molecular H_2 surrounding the PN halo in clumps. Because of self-shielding, these clumps would not become fully ionized, as seen, for example, in the Helix nebula (Huggins et al. 1992).

A36's core must be optically thin to hydrogen-ionizing photons, either because of its small column density or because it is porous and the many windows to the external ISM allow ionizing photons to escape. Evidence for the latter is A36's helical shape (Hua & Nguyen-Trong 1983). If a large fraction of PNe are as leaky as A36, then PNe could be an important contributor to the ionization budget of the warm ionized medium (WIM). As a function of height above the Galactic plane, Z , PNe may become increasingly more significant compared with O-type stars because PNe have a much larger scale height, 250 ± 50 pc, than O-type stars, 50 pc (Zijlstra & Pottasch, 1991 and Reed 1997, respectively).

Terzian (1980) estimates that 80% to 90% of the ionizing photons emitted by PN nuclei escape from the PN into the ambient ISM. Terzian (1974) uses the data of Cahn & Kaler (1971) to estimate that the number of ionizing photons that escape from PNe in the ISM near the Sun is $(2.5\text{--}6.5) \times 10^{49}$ photons s^{-1} kpc^{-3} , depending on assumptions about the size and luminosity of the central stars. For a scale height of 250 pc, the ionizing power available from PNe is as much as 7×10^{-5} ergs s^{-1} cm^{-2} , which is nearly equal to the amount required to keep the WIM ionized, 9×10^{-5} ergs s^{-1} cm^{-2} (Reynolds 1984). In fact, Reynolds (1984) foresaw the main result of this paper when he wrote, "High angular resolution maps of the diffuse $H\alpha$ background in regions which contain planetary nebulae and hot white dwarf stars may reveal the surrounding Strömgren spheres... and thus may help to determine the importance of these objects for the ionization of the interstellar medium." Indeed that is precisely how we discovered the

halo of A36, but its halo appears to be limited in extent to a radius of ~ 10 pc. It could be that A36 has a larger, fainter halo that even our observations cannot detect; that is, it is possible that the halo we observe is itself leaking ionizing photons farther into the ISM. Terzian (1974) estimates the local density of optically thin PNe to be 50 kpc^{-3} ; equivalently, 2×10^{-4} of the volume of the local ISM is within 10 pc of one of the those optically thin PNe. Thus, if A36's 10 pc radius is indeed a limit to the ionization from its central star, PNe of this kind cannot ionize most of the volume of the ISM. Based on only this single PN, we cannot assess the fraction of PNe that leak as large a share of their ionizing flux as does A36.

The Zanstra temperature, measured using hydrogen emission lines from only the core of A36, will significantly underestimate the effective temperature of the central star because this method ignores the flux from the halo, which is 30 times larger than that of the core. Indeed, Kaler et al. (1990) derived a hydrogen Zanstra temperature of 26,000 K and a He II Zanstra temperature of more than 73,000 K. They attributed the difference to the nebula (i.e., the core) being optically thin to hydrogen Lyman continuum; our detection of the halo confirms that hypothesis. Of the 68 PNe studied by Kaler et al. (1990), only one, Abell 15, has a lower ratio of hydrogen to helium Zanstra temperatures than Abell 36.³

4. SUMMARY

A 5° diameter halo is observed in $H\alpha$ around the planetary nebula Abell 36. Based on velocity-resolved $H\alpha$ spectra, the halo appears to be ambient interstellar gas ionized by the central star of the Abell 36. The $H\alpha$ luminosity of the halo is 30 times greater than that of the PN itself. Two solid results are (1) Abell 36 leaks a significant fraction of its ionizing radiation into the ISM; and (2) previous estimates of its hydrogen Zanstra temperature must have correspondingly underestimated the star's effective temperature. Observations of additional PNe with similar or better sensitivity may permit us to measure the extent to which the diffuse ISM is ionized by leaky PNe.

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³ Our $H\alpha$ survey also shows a halo around Abell 15; it is not as bright or as large in angular size as the halo of A36 described here.

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