VARIABILITY IN PROTO-PLANETARY NEBULAE. I. LIGHT CURVE STUDIES OF 12 CARBON-RICH OBJECTS

BRUCE J. HRIVNAK, WENXIAN LU, RICHARD E. MAUPIN1, and BRADLEY D. SPITZBART2
Department of Physics and Astronomy, Valparaiso University, Valparaiso, IN 46383, USA; bruce.hrivnak@valpo.edu, wen.lu@valpo.edu
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ABSTRACT

We have carried out long-term (14 years) V and R photometric monitoring of 12 carbon-rich proto-planetary nebulae. The light and color curves display variability in all of them. The light curves are complex and suggest multiple periods, changing periods, and/or changing amplitudes, which are attributed to pulsation. A dominant period has been determined for each and found to be in the range of ∼150 days for the coolest (G8) to 35–40 days for the warmest (F3). A clear, linear inverse relationship has been found in the sample between the pulsation period and the effective temperature and also an inverse relationship between the amplitude of light variation and the effective temperature. These are consistent with the expectation for a pulsating post-asymptotic giant branch (post-AGB) star evolving toward higher temperature at constant luminosity. The published spectral energy distributions and mid-infrared images show these objects to have cool (200 K), detached dust shells and published models imply that intensive mass loss ended 400–2000 years ago. The detection of periods as long as 150 days in these requires a revision in the published post-AGB evolution models that couple the pulsation period to the mass loss rate and that assume that intensive mass loss ended when the pulsation period had decreased to 100 days. This revision will have the effect of extending the timescale for the early phases of post-AGB evolution. It appears that real time evolution in the pulsation periods of individual objects may be detectable on the timescale of two or three decades.

Key words: planetary nebulae: general – stars: AGB and post-AGB – stars: evolution – stars: mass-loss – stars: oscillations – stars: variables: general

Online-only material: machine-readable table

1. INTRODUCTION

Proto-planetary nebulae (PPNs) are objects in transition between the asymptotic giant branch (AGB) and planetary nebula (PN) phases of stellar evolution. In this phase, the high AGB mass loss has ended and the star is surrounded by a detached, expanding shell of gas and dust. Prior to the Infrared Astronomical Satellite (IRAS) satellite in 1983, this phase remained as an observational “missing link” in the post-main-sequence evolution of stars of intermediate (1–8 M☉) mass. However, the use of the IRAS database has allowed the identification of PPNs on the basis of their infrared excesses and the colors of their circumstellar dust shells (Parthasarathy & Pottasch 1986; van der Veen et al. 1989; Hrivnak et al. 1989). This has led to the identification of ∼50 PPNs and an equal number of additional candidates (Hrivnak et al. 1994; Meixner et al. 1999; Ueta et al. 2000; García-Lario et al. 1997). They show a double-peaked spectral energy distribution (SED), with a peak in the mid-infrared from re-radiated emission from the circumstellar dust and a peak in the visible–near-infrared from the reddened photosphere. The spectral types range from B0 to K0. Reviews of the properties of PPNs have been published by Kwok (2000) and Hrivnak (2003) and they are included in the more general review of post-AGB stars by Van Winckel (2003).

Millimeter radio observations of CO, OH, and HCN have revealed the oxygen-rich or carbon-rich chemistry of the circumstellar shells (Likkilä 1989; Likkilä et al. 1991; Omont et al. 1993).

2 Present address: Smithsonian Astrophysical Observatory, High Energy Astrophysics, 60 Garden Street, MS-34, Cambridge, MA 02138, USA; bspitzbart@cfa.harvard.edu.

High-resolution visible spectroscopy has shown the objects to be iron-poor and led to the determination of the chemistry of the photospheres (Van Winckel 2003). High-resolution imaging with the Hubble Space Telescope (HST) has revealed the morphology of the nebulae, which are generally elliptical or bipolar with sizes up to a few arcseconds in radius (Ueta et al. 2000; Su et al. 2001; Sahai et al. 2007; Siődmiak et al. 2008).

We are carrying out a long-term study of the variability of PPNs. It initially began with radial velocity monitoring to search for possible binary companions. This was motivated, in part, by the idea that a binary companion could cause the dusty torus seen in bipolar PPNs, which apparently restricts the outflow and results in the bipolar morphology (Livio & Soker 1988). The results of this initial study did not reveal any binaries, but did reveal periodic velocity variations (Hrivnak & Lu 2000; Hrivnak 2009).

The radial velocity monitoring was followed-up by the initiation of a study of the light variations in PPNs, which has been ongoing for the past 15 years. We identified an initial sample of ∼40 PPN candidates and have monitored them for light variability. All of the PPNs are found to be light variables, and the preliminary results have been presented (Hrivnak & Lu 2000, 2007; Hrivnak et al. 2002). Arkhipova and collaborators (e.g., Arkhipova et al. 2000) have also presented the results of their light curve studies of several PPNs.

The results of our ongoing studies will be published in a series of papers. In this initial publication, we focus on 12 carbon-rich PPNs. We present in detail our observing program and discuss the observed light curves, which we investigated for periodicity. The results are then discussed in the broad context of post-AGB variability and evolution. In the next two papers in this series, radial velocity data are presented for four of the brightest of these 12 PPNs, and together they are used in the interpretation.
of the discovered pulsational variability (B. J. Hrivnak et al. 2010a, in preparation, 2010b, in preparation).

### 2. PROGRAM OBJECTS

The program objects are listed in Table 1. They are all relatively bright, \( V = 8 \) to 14 mag, and thus are accessible to study with a small telescope. All of the targets with the exception of IRAS 19500—1709 have been imaged with the HST and all but one show elongated nebulae and faint halos with the central stars visible (Ueta et al. 2000; Sahai et al. 2007; Siódmiak et al. 2008). Only for AFGL 2688 is the central star not visible; this object is seen in visible light only by scattering from its bipolar lobes and halo. About half of the targets have published mid-infrared images taken with 6–10 m telescopes (Kwok et al. 2002; Ueta et al. 2001; Clube & Gledhill 2004, 2006; Morris & Sahai 2000).

All 12 of the objects appear to be bona fide PPNs. They all have double-peaked SEDs and their spectra are classified as \( F \rightarrow G \) supergiants. Their carbon-rich nature was first recognized by the detection of \( C_2 \) and \( C_3 \) absorption in their visible spectra (Hrivnak 1995; Bakker et al. 1997). This has been confirmed with higher resolution abundance studies, which find an average value of \( C/O = 1.6 \) (Van Winckel & Reyniers 2000; Reddy et al. 2002). These studies find the objects to be slightly metal poor, \([\text{Fe/H}] = -0.7\), with high abundances of \( s \)-process elements such as \( Y, Ba, Ce, \) and \( Nd ([\text{Fe}/\text{Fe}] = 1.5) \), which are the results of nucleosynthesis and the third dredge-up during the AGB phase. Infrared spectra have shown these objects to display the aromatic infrared bands (AIBs) in emission at 3.3, 6.2, 7.7, 8.6, and 11.3 \( \mu \text{m} \) and aliphatic emission bands at 3.4 and 6.9 \( \mu \text{m} \) (Hrivnak et al. 2000, 2007), commonly attributed to polycyclic aromatic hydrocarbon (PAH) molecules. Also seen in their mid-infrared spectra are a broad emission feature at 20.1 \( \mu \text{m} \) (the “21 \( \mu \text{m} \)” emission feature; Volk et al. 1999; Hrivnak et al. 2009) and a very broad emission feature around 30 \( \mu \text{m} \) (the “30 \( \mu \text{m} \)” emission feature; Volk et al. 2002; Hony et al. 2002), which are found only in carbon-rich evolved objects, particularly PPNs. These spectroscopic properties are summarized in Table 2. (See Hrivnak et al. (2008) for a more detailed table of properties.)

Our object list composes an almost complete sample of known carbon-rich PPNs north of decl. \( -20^\circ \) and brighter than

### Table 1

List of C-rich PPNs Observed

| IRAS ID   | GSC ID | 2MASS ID | R.A. (2000.0) | Decl. (2000.0) | \( l (^\circ) \) | \( b (^\circ) \) | V (mag) | Sp.T. | Other ID |
|-----------|--------|----------|--------------|---------------|---------------|-------------|--------|------|---------|
| 02296+3429 | 03018+0014 | J02295805+0017 | 02:29:58.0 | +00:17:05.0 | -8.2 | 15.6 | 8.4 | G8 | ... |
| 05113+1347 | 05140775+350828 | J10140775+350828 | 10:14:07.8 | +35:08:28.0 | 13.5 | 12.7 | 12.4 | G9 | ... |
| 03454+0852 | 03565506+0854087 | J03565506+0854087 | 03:56:55.1 | +08:54:09.0 | 19.2 | 12.1 | 13.6 | G9 | ... |
| 07134+1005 | 07016105+0959480 | J07161025+0959480 | 07:16:10.3 | +09:59:48.0 | 206.7 | 10.0 | 8.2 | F5 | HD 56126, CY CMi |
| 07430+1115 | 07455139+1108196 | J07455139+1108196 | 07:45:51.4 | +11:08:29.0 | 208.9 | 17.1 | 12.6 | G9 | ... |
| 19500—1709 | 06317—0218 | J19525269—1701503 | 19:52:52.7 | -17:01:50.0 | 24.0 | 21.0 | 8.7 | F3 | HD 187885, V1522 Sgr |
| 20000+3239 | 02674—02983 | J02015951+324728 | 20:01:59.5 | +32:47:33.0 | 69.7 | 12.3 | 13.3 | G8 | ... |
| AFGL 2688a | 02713—02983 | J20015951+324728 | 20:01:59.5 | +32:47:33.0 | 69.7 | 12.3 | 13.3 | G8 | ... |
| 22223+4327 | 03212—00676 | J22234142+4343109 | 22:24:31.4 | +43:43:11.0 | 96.8 | 11.6 | 9.7 | G0 | DO 41288, V448 Lac |
| 22272+5435 | 03987—01344 | J22291039+5451062 | 22:29:10.4 | +54:51:06.0 | 103.3 | 2.5 | 9.0 | G5 | HD 235858, V354 Lac |
| 23304+6147 | 04284—00918 | J23324749+6203491 | 23:32:44.8 | +62:03:49.0 | 113.9 | 6.0 | 13.1 | G2 | ... |

Notes.

\( a \) Refers to the Hubble Space Telescope Guide Star Catalog.

\( b \) Coordinates from the 2MASS Catalog.

\( c \) Listed in the IRAS Faint Source Reject File (thus the “Z”) but not in the Point Source Catalog.

\( d \) Not included in the IRAS Point Source Catalog.
made together. The typical annual observing schedule involved frequent observations of the objects available in the summer and fall and infrequent observations during the winter and spring. Unfortunately, a defect developed in the V filter in 2000 that remained undetected for a long time. This has led us to reject all of the V data from 2,451,600 to 2,452,508 (2000 February 25 to 2002 August 21), resulting in a gap in the V light curves during that interval.

Integration times were adjusted with a goal of obtaining a precision of $\sigma \leq \pm 0.01$ mag. This precision was obtained for all but the faintest sources; integration times were limited to a maximum of ~6 minute due to lack of a guiding system for the telescope.

The observations were reduced using standard procedures in IRAF\(^3\) to remove cosmic rays, subtract the bias, and flat field the images. Aperture photometry was carried out, using an aperture of 11″ diameter. This accommodated the seeing quality of the site, which was typically ~3″. Only in the case of the fainter, southern lobe of AFGL 2688 ("Egg" nebula) was a smaller aperture (7″) used; this was to avoid contamination by the brighter northern lobe of this large, bipolar nebula.

Standardized photometry of several of these PPNs was carried out at the VOU on several nights using stars from the list of Landolt (1983). We had previously obtained standardized photometry of most of them as part of our larger studies of PPNs and these were previously published. We have listed all of these photometric results in Table 3. Many have very red colors due to reddening by their circumstellar dust.

### Table 3

| IRAS ID | V  | B−V | V−R | R−I | V−I | HJD−2,400,000 | Ref. |
|---------|----|-----|-----|-----|-----|---------------|-----|
| Z02229+6208 | 12.09 | 2.83 | 1.68 | 1.49 | 3.17 | 1993 Oct 27 | 1 |
| 04296+3429 | 14.21 | 1.99 | ... | ... | 2.57 | 1988 Oct 18 | 2 |
| 05113+1347 | 12.41 | 2.13 | ... | ... | 2.15 | 1989 Oct 01 | 3 |
| 05341+0852 | 15.55 | 1.81 | 1.09 | 1.03 | 2.12 | 1995 Sep 13 | 1 |
| 07134+1005 | 13.72 | 2.77 | ... | ... | 3.01 | 1989 Oct 18 | 3 |
| 07430+1115 | 12.62 | 1.86 | 0.99 | 0.94 | 1.93 | 1993 Oct 27 | 1 |
| 19500−1709 | 8.67 | 0.52 | ... | ... | ... | 1987 Sep 04 | 4 |
| ... | ... | ... | ... | ... | ... | ... | ... |
| AFGL 2688 | ... | ... | ... | ... | ... | ... | ... |
| 22223+4327 | 9.69 | 0.92 | 0.54 | 0.52 | 1.06 | 1989 Aug 24 | 3 |
| 22272+5435 | 8.68 | 2.00 | ... | ... | 1.96 | 1988 Oct 18 | 5 |
| 33040+6147 | 13.06 | 2.31 | ... | ... | 2.63 | 1988 Oct 18 | 2 |

Notes. Uncertainties in the brightness and color are ±0.01–0.02 mag.

\(^a\) Magnitudes of the PPNs on the standard $BVRI$ system at the time of the observations.

\(^b\) References for our previously published photometry: (1) Hrivnak & Kwok 1999; (2) Hrivnak & Kwok 1991a; (3) Kwok et al. 1995; (4) Hrivnak et al. 1989; (5) Hrivnak & Kwok 1991b.

Since our goal was to investigate variability in these PPNs, the observing program was organized around differential photometry of the candidates with respect to non-variable comparison stars in each field. This allowed us to collect data on the many non-photometric nights available at our site. A set of three comparison stars was established in each PPN field. The comparison stars were chosen in such a way as to minimize the standard errors in the differential magnitudes. For the fainter PPNs, they ranged from a little to a lot brighter and for the brighter PPNs they were a lot fainter than the PPNs; for the bright PPNs, we were more limited in our choices. Given the redness of our highly reddened PPNs compared to the comparison stars, the color matches of the PPNs and the comparison stars were usually not very close except for the F spectral type PPNs. The constancy of the primary comparison star C1 in each field was established over this interval. In a few cases, small variability in C2 or C3 is indicated. The level of constancy of the comparison stars C1 with respect to C2 is displayed in the subsequent light curve figures. The identity of the comparison stars and their standardized photometric magnitudes (when available) are listed in Table 4.

The differential $V$, $R$, and $(V−R)$ measurements of each PPN with respect to its primary comparison star C1 were transformed to the standard magnitude system and are listed in Table 5. Although in many cases we do not have a simultaneous set of $V$ and $R$ observations, we were able to carry out the standardization as follows. The color coefficients for standardization are small, $0.030$ for $V$ and $0.049$ for $R$, and thus our instrumental differential magnitudes are close to the standard system. Since none of the program stars vary much in color, $\Delta(V−R) \leq 0.12$ mag (except 0.18 mag for IRAS 05113+1347), a simple zero-point correction will bring the differential magnitudes close to the standard system. However, since there is a correlation between brightness and color (see Section 4.2), we were able to use this to make a very good approximation to correct for the star’s color at each observation. Differential extinction was small and was not applied to the observations. Uncertainties were calculated for the differential measurements and are shown in the light curve plots to follow. We have not listed them in Table 5, but to give an idea of the precision of the observations, we have tabulated the maximum and average uncertainties for each PPN in Table 6, along with the number of observations.

### 4. RESULTS

#### 4.1. Discussion of Individual Objects

The objects are discussed individually in the following text. We begin with the clearest cases of periodic variability and proceed in order of right ascension, beginning with IRAS 22223+4327.

IRAS 22223+4327: This object displays a light variation with a clear cyclical pattern of moderate amplitude during each year, superimposed on a general dimming of the object. The individual differential observations are of good precision ($\sigma (V) \leq 0.008$ mag). The light curves show an overall monotonic decrease in brightness by $\sim 0.16$ mag in 14 years. Visual inspection of the light curves suggests a period to the cyclical variation of $\sim 90$ days. The full range in brightness varies from season to season, with a maximum (peak-to-peak) in $\Delta V$ of 0.21 mag (1997–1998) and a minimum of 0.09 mag (2002–2003 and 2006–2007). An even greater brightness range is present in the 2000–2001 and 2001–2002 observations as documented in $\Delta R$, from 0.065 (also in 2006–2007) to 0.235 mag.

\(^3\) IRAF is distributed by NOAO, operated by the Association for Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
The seasonal variations are somewhat reminiscent of a beat period, suggesting a second period similar to the first. The color \( \Delta(V - R) \) varies over a range of 0.06 mag, and is systematically redder when the object is fainter in its cyclical variation. A small seasonal change in color is seen over the past four seasons, with the system slightly redder (0.01–0.02 mag) when dimmer.
Figure 1. Plot showing the differential light and color curves of IRAS 22223+4327. In the upper left panel are the entire curves and in the three other panels the curves are shown on expanded scales covering five years each. The error bars are included with the data in these expanded plots. Also shown in the upper left panel is the differential V light curve of the primary (C1) with respect to the secondary (C2) comparison stars on the same scale as the PPN light curves. Zero-point offsets are added to conveniently show all three light curves on the same plot.

Table 6

| IRAS ID        | Number of Observations | Maximum Uncertainty | Average Uncertainty |
|----------------|------------------------|---------------------|---------------------|
|                | ∆V ∆R ∆(V−R)          | σ(∆V) σ(∆R) σ(∆(V−R)) | σ(∆V) σ(∆R) σ(∆(V−R)) |
| Z02229+6208    | 130 88 62              | 0.013 0.010 0.014  | 0.005 0.003 0.006  |
| 04296+3429     | 70 39 28               | 0.030 0.016 0.028  | 0.020 0.010 0.020  |
| 05113+1347     | 78 37 31               | 0.014 0.009 0.017  | 0.008 0.005 0.009  |
| 05341+0852     | 67 35 31               | 0.025 0.011 0.026  | 0.014 0.008 0.017  |
| 07134+1005     | 89 58 48               | 0.010 0.008 0.008  | 0.004 0.004 0.005  |
| 07430+1115     | 73 47 39               | 0.010 0.008 0.010  | 0.006 0.003 0.006  |
| 19500−1709     | 181 125 98             | 0.007 0.007 0.008  | 0.003 0.003 0.003  |
| 20000+3239     | 213 173 131            | 0.017 0.012 0.020  | 0.010 0.005 0.011  |
| AFGL 2688-N    | 135 101 75             | 0.011 0.010 0.015  | 0.006 0.005 0.007  |
| AFGL 2688-S    | 124 99 69              | 0.020 0.018 0.024  | 0.011 0.008 0.012  |
| 22223+4327     | 267 212 160            | 0.008 0.008 0.011  | 0.003 0.003 0.004  |
| 22272+5435     | 248 189 132            | 0.008 0.008 0.011  | 0.004 0.004 0.006  |
| 23304+6147     | 197 163 111            | 0.020 0.020 0.023  | 0.011 0.009 0.013  |

Note. *a* The maximum or average uncertainty in a single differential measurement.

In a companion paper (B. J. Hrivnak et al. 2010a, in preparation, hereafter Paper II), this periodic light curve is analyzed together with the observed velocity curve to better understand the pulsations in the object. The light curves are discussed in more detail in that paper.

**IRAS 22227+5435** (Figure 2): This object displays a cyclical variation in brightness, but with a large range in amplitudes, varying in ∆V from a maximum 0.48–0.49 mag in 1998–1999 and 2007–2008 to a minimum 0.22 mag in 1995–1996, with a full range of 0.53 mag. The individual differential observations are of good precision (σ(V) ≤ 0.008 mag). The observed range in R is not so great but there are fewer observations. The mid-range value changes slightly from season to season over a range of ~0.10 mag in V. A period ~130 days is suggested by visual inspection of the light curves. The seasonal variations are reminiscent of a beat period, as was seen in IRAS 22223+4327. The color varies systematically with brightness—it is redder when fainter—with a typical seasonal range of 0.08 mag and a
This object is also analyzed together with the observed radial velocity curve in a companion paper with IRAS 22223+4327 (Paper II).

**IRAS 23304+6147** (Figure 3): This object displays a regular cyclical variation in light, although in the first and fifth seasons it appears as if the variation is damped out over approximately one cycle. The object is relatively faint \((V = 13.1)\) and consequently the error bars are relatively large (see Table 6; typically \(\pm 0.011\) mag in \(V\), \(\pm 0.009\) mag in \(R\), \(\pm 0.0013\) mag in \((V - R)\)). The variation appears to have a period of \(\sim 80\) days and a peak-to-peak maximum of 0.20 mag in \(V\) and 0.16 in \(R\). The object is redder when fainter, but the typical seasonal color range is only 0.06 mag (maximum of 0.10 mag). There appears to be perhaps a slight change in color over the 14 year observing interval, with the object becoming bluer by 0.02 mag in \((V - R)\).

**IRAS 202229+6208** (Figure 4): This object displays large, long-term variations of up to 0.54 mag \((V)\) in a season. Measuring the time between successive minima results in cycle lengths of \(\sim 130\) to \(\sim 160\) days. The light curve varies in appearance from cycle to cycle, with a suggestion that minima alternate between deeper and shallower ones, but this does not appear to follow a strict pattern. The object is redder when fainter. The maximum color range in a season is 0.06 mag, but some of the early seasons with large variations in \(V\) have few \(R\) observations and the color is consequently poorly sampled. The full range in \(V - R\) is 0.09 mag, and it appears that the overall color of the system was getting slightly bluer (by 0.03 mag) from 1995 to 2007.

**IRAS 04296+3429** (Figure 5): This object is one of the faintest targets in the present observing program \((V = 14.2)\), and the uncertainties are consequently large, particularly in \(V\). This is also seen in the scatter in the differential magnitudes of the comparison stars, since all of the stars in the field are relatively faint \((V \geq 13.2\) mag) for a 6 minute exposure. The system appears to show a monotonic increase in brightness of 0.10 mag in \(V\) from 1994–1995 to 2006–2007. The increase is less in \(R\), but the number of observations is smaller. The variation within a season ranges from 0.05 to 0.13 mag. The large uncertainty compared to the range prevents us from saying much about the light curve variability or correlation with color. However, the object appears to be redder when fainter. Note that we have begun to observe this object at higher precision (with guiding) in a new observing program designed for fainter targets.

**IRAS 05113+1347** (Figure 6): This object clearly varies, with peak-to-peak variations of 0.67 \((V)\) and 0.49 \((R)\) mag seen in 2005–2006. The variation appears to be cyclical, with cycle length of \(\sim 120–130\) days, and the amplitude of the variation clearly changes. The color changes over a range of 0.18 mag, seen also in 2005–2006, and the system is redder when fainter.

**IRAS 05341+0852** (Figure 7): The object is faint \((V = 13.6\) mag), and the uncertainties are consequently large. This object displays a peak-to-peak variation of 0.18 mag, with the overall brightness appearing to increase by 0.09 mag beginning in 2005. A suggestion of a cyclical variation is seen in several seasons, with a maximum seasonal range of 0.13 mag \((1997–1998)\) and a suggestion of a period of \(\sim 70\) days in 1997–1998 and 1998–1999. However, there are not a lot of observations. The color changes over a range of 0.08 mag and is generally redder when fainter, although the uncertainty in the data is large.

**IRAS 07134+1005** (Figure 8): This object clearly varies, with a typical seasonal range of 0.09 mag \((V)\) and a maximum of twice that value in 1995–1996. The variations generally look cyclical, but no consistent period is obvious by visual inspection. The object is slightly redder when fainter, but with a peak-to-peak range of only 0.045 mag.

The light curve of this object is analyzed together with the observed radial velocity curve in a second companion paper (B. J. Hrivnak et al. 2010b, in preparation, hereafter Paper III).

**IRAS 07430+1115** (Figure 9): The object clearly varies, with ranges (peak-to-peak) of 0.32 mag in \(V\) and 0.27 in \(R\), although part of the apparent difference in ranges may be due to the fewer \(R\) observations in the early years. The variations appear to be cyclical, with a typical seasonal range of 0.15–0.23 mag \((V)\) and a cycle of \(\sim 150\) days. The overall stellar brightness also appears to change, dimming by \(\sim 0.1\) mag between 1995 and 1996 and then gradually increasing to the initial 1995 value by \(\sim 2004\). The color is redder when fainter, with a color range of 0.08 mag. Some of the color change may correspond to the long-term seasonal change in brightness and the rest to the cyclical variation, but these are hard to distinguish given the small number of color data points.

**IRAS 19500–1709** (Figure 10): The star shows a cyclical seasonal variation with changing amplitude. In addition, the overall light level of the star has changed. From 1993–1998, the mean brightness was approximately constant. However, in 1999, it was found to be fainter by 0.12 mag in \(V\) and 0.10 mag in \(R\). It gradually brightened by about 0.19 mag in \(V\) and 0.14 mag in \(R\) from then through 2004, and it has been at approximately the same mean brightness through 2008. As is apparent by these brightness values, the color of the star also changed during this time, getting redder in \((V - R)\) by 0.02 mag when the system dimmed and then getting bluer by 0.04 mag when it brightened. (Note that photometric observations of this object by Arkhipova et al. 2000 from 1993 to 1999 show a similar light and color curve change in 1999.) The seasonal cyclical variations show amplitudes varying from 0.05 to 0.13 mag in both \(V\) and \(R\). The maximum color range in a season is only 0.04 mag; there is a slight tendency for the object to be slightly redder when fainter. Visual inspection indicates cycle lengths of 30–35 days.

This object is analyzed together with the observed radial velocity curve in a companion paper with IRAS 07134+1005 (Paper III).

**IRAS 20000+3239** (Figure 11): The light curve shows a large variation from season to season and within a season. A cyclical variation is seen over the first three seasons (1994–1996) with deeper and shallower local minima, somewhat similar to those seen in RV Tau variables. However, there does not appear to be a distinct pattern of deeper and shallower minima. The variability range changes from year to year. A cyclical variability is seen during the first three seasons, while in the next two seasons (1997–1998), the brightness appears to rise relatively quickly to a plateau value. The amplitude of the cyclical variation then generally begins to increase to a maximum range in 2003 of 0.59 mag \((V)\), but it varies quite a bit from year to year. The maximum brightness level of the object is greater after 1999 than before. The variations in \(R\) are similar. Color variations

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4 The letter Z is added at the beginning because the object is absent from the IRAS Point Source Catalog but is present in the Faint Source Reject File. See Hrivnak & Kwok (1999) for a discussion of the identification of this object. Note that we have omitted the Z in some of the figure labeling.
Figure 2. Plot showing the differential light and color curves of IRAS 22272+5435, plotted similar to Figure 1.

Figure 3. Plot showing the differential light and color curves of IRAS 23304+6147, plotted similar to Figure 1.
Figure 4. Plot showing the differential light and color curves of IRAS Z02229+6208, plotted similar to Figure 1.

Figure 5. Plot showing the differential light and color curves of IRAS 04296+3429, plotted similar to Figure 1.
Figure 6. Plot showing the differential light and color curves of IRAS 05113+1347, plotted similar to Figure 1.

Figure 7. Plot showing the differential light and color curves of IRAS 05341+0852, plotted similar to Figure 1.
Figure 8. Plot showing the differential light and color curves of IRAS 07134+1005, plotted similar to Figure 1.

Figure 9. Plot showing the differential light and color curves of IRAS 07430+1115, plotted similar to Figure 1.
Figure 10. Plot showing the differential light and color curves of IRAS 19500−1709, plotted similar to Figure 1.

Figure 11. Plot showing the differential light and color curves of IRAS 20000+3239, plotted similar to Figure 1.
range over 0.12 mag, with a general trend of being redder when fainter. The individual observations are of good precision, even though the object is faint ($V = 13$ mag), with typical values of $\sigma(V) = 0.010$ mag, $\sigma(R) = 0.005$ mag, and $\sigma(V-R) = 0.011$.

AFGL 2688 (Figures 12 and 13): This is the well-known bipolar PPN the Egg Nebula and both lobes can be seen and measured separately. The southern (S) lobe is fainter by $\sim 0.015$ mag. In carrying out aperture photometry, in order to avoid contamination by the northern (N) lobe, a smaller aperture (7″ diameter) was used. Both lobes show a general trend of increasing brightness over the 14 seasons of observation. Both lobes gradually increase in brightness by $-0.22$ mag ($V$) and get bluer by $-0.03$ mag ($V-R$). The N lobe also shows a cyclical variation within a season, with a peak-to-peak range varying between 0.04 and 0.18 mag ($V$) and averaging $-0.10$ mag. The variation in $R$ is similar but slightly smaller. No obvious periodicity stands out from visual inspection of the light curve. The color is slightly redder when fainter within a season, reaching a maximum variation of 0.05. The data from the fainter S lobe are less precise. They also show a cyclical variation that appears to be over a somewhat larger range of up to $-0.30$ mag ($V$) and $-0.07$ mag ($V-R$) in a season. However, the variations in the two lobes do not appear to be correlated.

4.2. Trends in the Light Curves

Several of the objects also show long-term trends in brightness over the observing interval. IRAS 22223+4327 decreased in $V$ brightness by $\sim 0.16$ mag in 14 years. IRAS 04296+3429 showed a monotonic increase in $V$ brightness of $\sim 0.10$ mag over 13 years. AFGL 2688, in both the N and S lobes, increased in $V$ brightness by $-0.22$ mag and got bluer by $-0.03$ mag over 14 years. This can be compared with an older, long-term study of the annual mean blue light curve of AFGL 2688 (N lobe) based on photographic plates. This showed a general brightening from 1920 to 1958 of $\sim 2.0$ mag followed by a more constant brightness through 1975 (Gottlieb & Liller 1976). Within a season a large spread in brightness was seen, indicating seasonal variation. This rate of increase in brightness of the annual mean blue light curve of AFGL 2688, $\sim 0.05$ mag yr$^{-1}$ (1920–1958) or $\sim 0.04$ mag yr$^{-1}$ (1920–1975), is three times as great as the rate that we find of $\sim 0.015$ mag yr$^{-1}$. It is more similar to the smaller rate of increase seen in the photographic light curve from 1968 to 1975. IRAS 05341+0852 displayed a brightness increase beginning in 2005 that amounted to $\sim 0.09$ mag ($V$) in four years. IRAS 19500–1709 showed a sudden drop in $V$ brightness of 0.12 mag in 1999 followed by a gradual increase over five years to a level $\sim 0.07$ mag brighter than the initial value. It also became redder by 0.02 mag when it suddenly became fainter, but gradually became bluer by 0.04 mag as it subsequently brightened.

All of the objects show a general correlation between brightness and color, being redder when fainter. This can be seen quantitatively in a plot of differential color, $\Delta(V-R)$ versus differential magnitude, $\Delta V$. These are shown in Figure 14, with a panel for each object except AFGL 2688-S. AFGL 2688-S shows a similar range in brightness and color as AFGL 2688-N, but with more scatter in the observations. However, the fainter S lobe is redder than the brighter N lobe by $\Delta(V-R) \approx 0.18$; this is presumably due to the greater extinction that causes the lobe to appear fainter. While for almost all of these PPNs, this correlation between color and brightness tracks the cyclical variations in the objects, this is not the case for IRAS 19500–1709 and AFGL 2688-N and 2688-S; in these objects most of the color change is associated with the long-term, seasonal light curve changes documented above and not the cyclical variations seen within a season. It can be seen that the objects with the largest range in color, IRAS 05113+1347, 20000+3239, 22272+5435, and 02229+6208, are the ones with the largest range in brightness.

5. PERIOD ANALYSIS AND RESULTS

5.1. Period Search Methods

The main goal of the program was to search for periodicity in the observed light curves. This was investigated using several programs commonly used to search for periods in unequally spaced data. We began with the CLEAN algorithm, which is based on a Fourier transform (Roberts et al. 1987). This was used to investigate a dominant period in the data sets. We further investigated the variability using the period analysis program Period04 (Lenz & Breger 2005). This latter program also uses a Fourier analysis, fits the variations with sine curves of calculated amplitudes, and can easily be used to search subsets of the data and to investigate multiple periods.

For the PPN light curves that show a general trend in their seasonal light curves, such as a monotonic decrease (e.g., IRAS 22223) or a sharp change (e.g., IRAS 19500), we removed the trend by normalizing the seasonal light curves to the average value for that season. For others that appear to show changes in the mean light level from season to season, we also investigated the effect on the period search of normalizing the data to the mean level.

In the analysis of the data, we investigated the $V$, $R$, and $(V-R)$ light curves separately. All of the objects show similar but not necessarily identical periods between the $V$ and $R$ light curves and with the $(V-R)$ color curves where the data are of good precision. These differences likely arise from two related effects. First, the data were not all taken in the same nights. The initial observations were only with the $V$ filter and the use of the $R$ filter was introduced only gradually over the first several years. Then for approximately 2.5 years there is an absence of $V$ data and only $R$ data are available due to a problem with the $V$ filter. Only since 2002 August 22 ($\sim 2002.6$) have the $V$ and $R$ observations been consistently observed on the same dates. The $V$ data thus span a longer time interval and they are more in number but they are missing for about two and a half years. Second, the period may be changing with time, and since the $V$ data are much more common in the early years, the resulting periods might be expected to differ. These differences are documented below for the individual sources. To investigate these differences further, for the objects with the most data, we also analyzed the periods in three subsets of the data: (1) the 1994–1999 $V$ light curve, (2) the 2002.6–2008 $V$ light curve, and (3) the 2002.6–2008 $R$ light curve. These results suggest that, at least for a few objects, the period is changing slightly, by a few percent.

The frequency spectrum from the CLEAN analysis and the phased light curve based on the dominant peak in the $V$, $R$, and $(V-R)$ data (where applicable) are shown for each of the PPNs in Figures 15, 16, and 17. To determine the uncertainties ($\sigma$) in the calculated period values, we employed the least-squares fitting function in Period04. The individual analyses are discussed below. In all cases, the results of the CLEAN and Period04 analyses agree to within 2$\sigma$. An overly conservative estimate of the uncertainty of the calculated period could be
Figure 12. Plot showing the differential light and color curves of AFGL 2688-N, plotted similar to Figure 1.

Figure 13. Plot showing the differential light and color curves of AFGL 2688-S, plotted similar to Figure 1.
Figure 14: Plot showing the change in color with change in brightness for each of the targets. A clear trend is seen for each of the PPNs, with the object being redder when fainter.

derived from the full width, half-maximum of the period peak. This was examined in several cases and found to have a value of \( \sim 10–20 \) times the least-squares uncertainty (\( \sigma \)). In the following discussion, we have listed the period values to the nearest day. The formal periods and uncertainties are listed in Table 7.

5.2. Results for Individual Objects

\textit{IRAS 22223+4327}: The monotonically decreasing brightness trend was first removed. The period analyses revealed very clear, strong peaks in the frequency. The \( V \) data show a strong peak at \( P = 88 \) days, with a secondary peak at 91 days; the \( R \) data show a strong peak at 91 days, and the \( (V - R) \) data show peaks at 88 days and 91 days. However, when we examine the data in subsets, for the 1994–1999 data, \( P(V) = 89 \) days and for the 2002–2008 data, both the \( V \) and \( R \) data are similar with two equally strong frequency peaks at \( P(V, R) = 91 \) and 86 days. Thus the data show the period to be in the range 86–91 days, with evidence of multiple periods. This encompasses the value of \( \sim 90 \) days determined by Arkhipova et al. (2003) based on \( UBV \) observations made over four seasons (1999–2002).

\textit{IRAS 22272+5435}: The period analyses show a very strong peak in each light curve, with \( P(V) = 132 \) days, changing
Figure 15. Plot showing the frequency spectrum and phased V light curve for each of the targets. There is generally one strong peak in the frequency spectrum from which we derived the period. The periods used are the first ones listed in Table 7 under the CLEAN analysis for this filter, and the 0.00 phase is based on the time of the first data point. The normalized light curves were used for the objects with large season-to-season trends: IRAS 04296+3429, 05341+0852, 07430+1115, 19500−1709, 22223+4327, and AFGL 2688-N lobe.
Figure 16. Plot showing the frequency spectrum and phased R light curve for each of the targets, similar to Figure 15. IRAS 04296+3429 and AFGL 2688-N had no dominant peak, so no phased light curve was plotted.

to $P(V) = 131$ days if we normalize the light curve for the slightly different seasonal means, and a second double peak at 124.9/127.7 days. For the $R$ data, $P(R) = 127$ days with a weaker peak at 132 days; the $(V - R)$ data show a dominant period of
127 days. If we investigate this in subsets, for the 1994–1999 data, $P(V) = 133$ days, and for the 2002–2008 data, both the $V$ and $R$ data yield the same period $P(V, R) = 128$ days. Thus for the object, the data show the period to be in the range 127–133 days.
with evidence for multiple or changing periods. These values differ significantly from the periods of 207 days and 145 days (secondary period) determined by Arkhipova et al. (2000) based on 72 observations in each of the $UBV$ filters made over nine seasons (1991–1999). This demonstrates the intrinsic variability of the light curves of these objects and the need for long-term studies to accurately determine their periods. Recently, Zsécs et al. (2009) determined a period of 131 days based on radial velocity observations, a value in good agreement with ours. These additional independent data sets will be combined in our follow-up study of this object (Paper II).

IRAS 23304+6147: The period analyses result in $P(V) = 85$ days and $P(R) = 85$ days, with a secondary period of 72 days ($V$) and 70 days ($R$). The ($V$–$R$) data set shows no dominant period. Examining the data in subsets yields generally similar results: $P(V) = 84$ and 72 days for the 1994–1999 $V$ light curve, $P(R) = 81$ days for the 2002–2008 $R$ light curve, but $P(V) = 67$ days with low amplitude for the 2002–2008 $V$ light curve. The reason for this deviant period value for the last data set is not clear (it does show a secondary period of 91 days), but the rest of the data give a consistent value for the dominant period $\sim 85$ days for this object.

IRAS 202229+6208: The period analyses result in similar periods in the two colors of $P(V, R) = 153$ days, with the same period when normalized. A longer period of $\sim 820$ days appears in the $V$ data, although it is much less significant when the data are normalized. A weaker peak of 137 days also appears in the data. The ($V$–$R$) color curve has a consistent peak at 153 days; the long period peak in the frequency spectrum is due to the trend in the color data and goes away when the color curve is normalized. An examination of the data in subsets shows periods of $P(V) = 152$ and 820 days for the 1994–1999 $V$ light curve and $P(V, R) = 136$ days for the 2002.6–2008 $V$ light curves, but these are less certain due to the small number of data points (<40) in each subset. Thus, the dominant period for the system appears to be $P = 153$ days. There is no evidence for a period of twice this value, as might be the case for an RV Tau star with alternate deep and shallow minima.

IRAS 04296+3429: The period analyses of the normalized data show no dominant period, but the strongest peak is at $P(V) = 71$ days with no strong peak in the smaller $R$ and ($V$–$R$) data sets. Thus, $P = 71$ days should be regarded as a tentative value.

IRAS 05113+1347: The period analyses result in a period of 133 days in $V$ and 138 and 128 days in $R$. There is no dominant period in the ($V$–$R$) data set. The data from 2002.6–2008 alone yield $P = 136$ days in both $V$ and $R$, with a larger amplitude than when the entire data sets are analyzed, but the sample size is small (<30). Thus, the period appears to be $\sim 133$ days.

IRAS 05341+0852: The period analyses were carried out on the normalized data. The $V$ data gives a clear period at 94 days. The $R$ data are very few in number most years, which makes normalization uncertain, except for the four-year span from 2003–2006. An examination of the $R$ data from 2003–2006 alone indicates $P = 93$ days, based on 26 data points. The small ($V$–$R$) data set possesses no dominant peak in the frequency spectrum.

IRAS 07134+1005: The period analyses show peaks at $P(V) = 35$ days and 44 days, $P(R) = 39$ and 50 days, and $P(V, R) = 35$ days (along with a longer period of 528 days, which does not appear in the more densely populated $V$ and $R$ data), but none of them is very strong. If we normalize the data to the mean light level, then $P(V) = 39$ days and $P(R) = 39$ days. Analyzing the data in subsets results in $P(V) = 44$ and 39 days for 1995–1999, $P(V) = 35$ days for 2002–2008, and $P(R) = 39$ and 35 days for 2002–2008, but the number of data points is small for each, 49, 40, and 39, respectively. It seems likely for this object that there are either several relatively closely spaced periods or that the period is switching from one value to another. The period value is found to be in the range 35–44 days, with a most probable value of $P \approx 39$ days.

This bright PPN has previously been studied for periodic variability. Barthés et al. (2000) found a main period of 36.7 days based on 89 radial velocities obtained over eight years and 36.9 days based on 87 photometric measurements made over seven seasons (1998–1996, with most in the first four seasons). These values are consistent with our results, and these data and ours will be combined in our subsequent detailed study of this object (Paper III).

IRAS 07430+1115: The period analyses were carried out on the normalized data. These resulted in two nearly equally probable periods in $V$, 136 days and 148 days, with the former slightly preferred based on the appearance of the resulting phased light curve. The $R$ data has its strongest peak at 99 days, with the second strongest at 136 days; the latter one agrees with the $V$ peak and gives a good phased light curve. There is no strong peak in the ($V$–$R$) analysis. Thus the best fit to the data, based primarily on the more numerous $V$ data, indicates that $P = 136$ days, with a secondary peak at 148 days. We are continuing observations of this target to better determine the period.

IRAS 19500−1709: The period analyses was carried out on the normalized data sets and indicated a period of 38 days in $V$, $R$, and ($V$–$R$). Other, weaker periods appear to also be present in the data. When the data were examined in subsets, we found the following: $P(V) = 51$ and 37 days for the interval 1994–1999; $P(V) = 42$ and 38 days for the interval 2002–2007; and $P(R) = 38$ days for the interval 2002–2007. The period of variation for this object appears to be less stable than for the longer period objects in this study. We conclude that the most dominant value of the period during our observing interval is 38 days, but there appear to be other periodicities in the data.

Arkhipova et al. (2000), based on their 1993–1999 $UBV$ light curves study, found periods of 97.4, 53.1, and 34.9 days, none of which were very strong. In our detailed study of the light and velocity of this object (Paper III), we will combine our data with that of Arkhipova et al. (2000) and with some additional unpublished photometric data in an effort to better understand the pulsational properties of this object.

IRAS 20000+3239: The light curve shows distinct variations in seasonal brightness. We began by analyzing the observed, un-normalized data. The period analyses indicate a well-determined period in $V$ at 153 days. The $R$ data also showed a period at 153 days; in addition, the frequency spectrum also shows a period of about seven years from an attempt to fit the seasonal brightness. The ($V$–$R$) color curve indicating $P = 155$ days. The $V$, $R$, and ($V$–$R$) light curve periods are similar when normalized, 153, 152, and 156 days, respectively. Examining the 2002–2008 light curves separately yields the same period values, but with larger amplitudes than found for the entire data sets. There is no evidence for a period twice as long. Thus, the light curves indicate that $P \approx 153$ days.

AFGL 2688: We investigated the presence of a period in the brighter, N lobe of this extended bipolar object. The light from the central star is completely obscured. The period analyses suggest a long period of about 600 days and slightly weaker periods of 93 and 87 days in $V$ and 62 and 89 days in $R$,
following the removal of the long-term brightening trend in the data. The ∼600 days periodicity shows up on the (V − R) frequency spectrum, along with several other weak peaks. We take the best estimate of the pulsation period of the star to be ∼90 days. This object bears continued monitoring to verify the reality of this and the longer period.

Note that the visible light that we are receiving from this object is light scattered toward us from the lobes. This makes the detection of a periodicity in the light of the central star more difficult since we are measuring the light of the object integrated over an area of the lobe. The HST image of the object (Sahai et al. 1998) shows the brighter portion of the N lobe to have a radial size of about 5″, and a measurement of the size of the lobe in our images shows the FWHM to be about 5″. Typical distance estimates range from 400 to 1500 pc. At an estimated distance of 1 kpc, 5″ subtends a size of about 30 light days. If we adopt the recent value of 420 pc derived from differential proper motion based on HST images (Ueta et al. 2006), then the bright part of the lobe subtends a size of ∼12 light days. In practice then, this light spread is convolved with the periodic variation from the star and thus diminishes the emitted profile of the light variation, making a periodic light variation less than ∼100 days difficult to measure.

5.3. Investigation of Possible Period Changes

Evidence for period changes was investigated in three of the targets possessing the most data and with relatively well-determined periods. We compared the period determined for the 1994–1999 interval with that determined for the 2002–2008 interval. For IRAS 22223+4327, the period changed from 89 days to two equally strong periods of 86.5 and 91.5 days, which have an average value of about 89 days. For IRAS 22272+5435, the period appeared to decrease from 133 to 128 days and for IRAS 23304+6147, the period appeared to decrease from 84 to perhaps 81 days. These latter two suggest perhaps a decrease of ∼4% between these two time intervals. However, these results are only tentative since the time interval is short, on the order of a decade, the sample is small, and these objects show evidence of multiple periods.

We will investigate this question of period change further for IRAS 22223+4327 and 22272+5435 in Paper II, where we include the results of other published photometric data for these two sources. We will also there investigate the evidence for multiple periods in these two systems that can lead to the appearance of a beat period. In addition, we are continuing the observations of all three of these PPNs to extend the time baseline.

6. DISCUSSION

The targets in this study are all post-AGB objects in transition between the AGB and PN phases in the evolution of intermediate-mass stars. It is known that AGB stars vary in brightness with large amplitudes due to pulsations as they evolve from Miras to long-period variables to OH/IR stars, losing mass at an increasingly high rate (Olofsson 2004; Hrivnak & Bieging 2005). Periods for these range from 100 to 2000 days. Once in the post-AGB phase, such stars evolve at constant luminosity toward higher temperatures. This is the state of our targets, which are evolving to higher temperatures and shorter periods, presently with spectral types ranging from ∼G8 to F3 and periods ranging from 153 to ∼38 days. Most of these PPNs have model atmosphere analyses based on high-resolution spec-troscopy, from which effective temperatures ($T_{\text{eff}}$) have been determined. These results are all summarized in Table 8. There exists a clear trend of period with spectral type; the coolest PPNs have a spectral type of ∼G8, an effective temperature of 5250–5500 K, and a pulsation period of ∼150 days. With a $T_{\text{eff}}$ range of 5250–8000 K, these objects span the temperature range of the instability strip for luminous variable stars and perhaps extend even a little hotter. This suggests that these objects also vary due to radial pulsation driven by the $\kappa$-mechanism (Ostlie & Carroll 1996) operating in the helium partial ionization zone.

In respect to spectral type and period, the PPNs in this study bear some resemblance to the RV Tau stars, which are also variable stars thought to be post-AGB stars of F–K spectral types and luminosity class of Ia–II. The RV Tau stars show alternately deep and shallow minima, with periods of approximately 15–75 days (or twice that between deep minima), and V amplitudes generally between 1 and 2 mag, although some have even larger amplitudes (Wahlgren 1993; Percy 2007). A few RV Tau stars with V amplitudes as low as 0.1 mag have been observed (Pollard et al. 1996). It has been found that RV Tau stars share a period–luminosity relationship with Type II Cepheids, as seen from studies in the LMC (Alcock et al. 1998). In the LMC study, it is also found that the longer period RV Tau stars have smaller amplitudes, the opposite of what we find in our PPN sample (see below), and that there is no relationship between period and color, while in our PPNs there exists a clear relationship between period and spectral type (see Table 8). The lack of distances and thus luminosities for these PPNs prevents us from investigating directly a period–luminosity relationship; however, the evidence in hand points more strongly to a period–temperature relationship based on the evolution of these objects across the H–R diagram. While the RV Tau stars also possess infrared excesses, they are generally much less than that seen in these PPNs, for which about half of the flux is detected in the mid-infrared. This difference in circumstellar material points to a difference in the initial masses, with these PPNs evolving from stars of higher initial mass than the RV Tau variables, which are thought to evolve from low mass stars. Thus these PPNs, in general, tend to have longer periods and smaller amplitudes than the RV Tau stars, without (in most cases) alternating differences in the depth of minima. Recent radial velocity studies indicate that a significant fraction of RV Tau stars (and other dusty post-AGB stars) may be binaries in which the circumstellar dust is maintained by the gravitational interaction of the companion (Van Winckel 2003, 2007). None of the PPNs have thus far been found to be radial velocity binaries (Hrivnak 2009). Future studies of an enlarged sample of PPNs can investigate further the similarities and differences with the pulsational light curves of RV Tau stars and other dusty post-AGB stars.

This observed upper limit to the PPN periods of ∼150 days bears upon models of the post-AGB evolution of intermediate-mass stars. Post-AGB stars evolve toward higher temperatures and the PN regime at rates that depend upon their envelope mass relative to their core mass. Evolutionary calculations show that the evolution from the tip of the AGB to the beginning of the PPN phase, from $T_{\text{eff}}$ of ∼3000 to ∼5000 K, will take much too

5 We define the start of the PPN phase as the time when the extensive AGB mass loss has ended and the envelope is effectively detached from the star. It is likely that there is still some ongoing mass loss but at a much lower rate. This definition is slightly different than that used in some post-AGB evolutionary calculations (i.e., Schönberner 1983; Blöcker 1995), which start at the time that the post-AGB mass loss has finished its non-abrupt decline from the extensive AGB mass loss rate and is just beginning a low, Reimers-like mass loss. This latter definition might thus exclude the cooler, longer period objects.
Table 7
Results of the Period Study of Carbon-rich PPNs

| IRAS ID      | CLEAN Analysis | Period04 Analysis |
|--------------|----------------|-------------------|
|              | P(days)        | P(days)           |                | P(days)       | P(days)       |                | P(days)       | P(days)       |                |
| Z03229+6208  | 153.0, 137.1, 813 | 153.3, 137.6, 152.8 | 153.0, 137.1 ± 0.4, 854 | 152.4 ± 1.2, 820, 153.3, 137.0 ± 0.6 | 153.3, 137.0 ± 0.6 | 136.1 ± 1.0, 136.0 ± 0.5, 152.6 ± 0.5 |                |                |
| 04296+3429a  | 71, ...        | ...               | 71, ...          | ...           | ...           | ...            | ...           |                |
| 05113+1347   | 133.1, 137.8, 127.8 | ...               | 133.0 ± 0.3     | ...           | ...           | ...            | ...           |                |
| 05341+0852c  | 93.8, 92.8b     | ...               | 93.9 ± 0.1      | ...           | ...           | 92.9 ± 0.8b    | ...           |                |
| 07134+1005   | 35.1, 44.4     | 35.0, 528         | 35.1, 44.5 ± 0.1c | 44.1, 38.9 ± 0.1c | ...           | 38.8 ± 0.1c, 38.7, 35.0 ± 0.1c | 35.0 ± 0.1c, ... |                |
| 07430+1115c  | 135.9, 148.5, 98.9, 136.2 | ...               | 135.8, 148.5 ± 0.3 | ...           | ...           | ...            | ...           |                |
| 19500–1709b  | 38.3, 38.4, 38.2, 30.3 | 38.3, 38.4, 45.4 ± 0.1c | 50.7, 36.8 ± 0.1c | 42.4, 38.2 ± 0.1c | 38.4 ± 0.1c | 38.2 ± 0.1c | 7.4, 30.5, 38.0 ± 0.1c |                |
| 20000+3239   | 152.6, 152.6, 155.0 | 152.7 ± 0.3       | ...             | 153.5 ± 0.8, 153.0 ± 0.5 | 153.3 ± 0.9, 155.0 ± 0.4 | 155.4 ± 1.2 |                |                |
| AFGL 2688-Nb | 93.0, 602      | 89.1, 595         | 93.2, 89.5 ± 0.2, 600 | ...           | 61.7, 89.1 ± 0.2, 595 | ...           | ...           |                |
| 22223+4327b  | 88.0, 90.8, 91.0 | 88.1, 91.0        | 87.8, 90.9 ± 0.1 | 88.8 ± 0.1 | 91.5, 86.5 ± 0.2 | 90.7 ± 0.1, 91.7, 86.4 ± 0.2, 87.8, 90.9 ± 0.2 | 89.2 ± 0.2 |                |
| 22272+5435   | 132.2, 124.9/127.7, 127.2, 127.5 | 132.0 ± 0.1     | 133.1 ± 0.4 | 128.1 ± 0.3, 127.7 ± 0.3 | 128.0 ± 0.3, 127.3 ± 0.2 | 127.6 ± 0.3 |                |                |
| 23304+6147   | 84.6, 85.0      | ...               | 84.6 ± 0.1      | 84.2 ± 0.2 | 66.8 ± 0.2 | 85.0 ± 0.1 | 81.5 ± 0.3 | ...           |                |
| Notes.       |                |                   |                  |                |                |                |                  |                |
| a Light curve trend removed before analysis. | | | | | | | | |
| b For the interval 2002–2006. | | | | | | | | |
| c The uncertainties appear to be unrealistically small and are rounded up to ±0.1 days. | | | | | | | | |
The tip of the AGB and there they abruptly begin a radiation-driven post-AGB phase at the point when the temperature is $T_{\text{eff}} \approx 5000$ K (e.g., Schönberner 1983). Various prescriptions for such ongoing mass loss have been applied (Vassiliadis & Wood 1994; Blöcker 1995). Blöcker (1995), in his models of post-AGB evolution, made the assumption that the extensive mass loss rate does not simply terminate abruptly at the end of the AGB phase, but rather that it decreases gradually in proportion to the decreasing radial pulsation period of the star. This dependence of mass loss on the pulsation period is quite reasonable since pulsation seems to be the mechanism driving mass loss through dust formation on the AGB (Bowen 1988). In most of his models, Blöcker assumed that the extensive mass loss rate began decreasing when the star had a pulsation period of 100 days and decreased down to a low Reimers mass loss rate as the period lowered to 50 days. He found from these models that the timescale for this evolution was relatively rapid, on the order of a several hundred years or less. This initial assumption was changed for one of his published models, in which he started the decrease in mass loss rate with the longer pulsation period of 150 days and decreased the rate as the period lowered to 100 days. In this later case, Blöcker found that the stellar evolution during this transition in mass loss rate happened much more slowly, $\sim$2800 year when beginning with $P = 150$ days as compared to $\sim$800 year when beginning with $P = 100$ days (with $M_{\text{ZAMS}} = 3.0 M_\odot$ and $M_{\text{core}} = 0.625 M_\odot$). Thus, this change to a longer initial period for the beginning of the decrease in extensive mass loss rate has the consequence of long ($\sim 10^5$ years depending upon the core mass) unless there is significant post-AGB mass loss until $T_{\text{eff}} \approx 5000$ K (e.g., Schönberner & Steffen 2007). About half of the PPNs in this sample have been imaged in the mid-infrared and their detached dust shells resolved, including IRAS 22272+5435 (Ueta et al. 2001) with a $G5$ spectral type. Based on Blöcker’s model, this longer initial pulsation period would imply that the transitional time from the end of the extensive AGB mass loss to the beginning of the ongoing low mass loss rate is a few thousand years rather than a few hundred years. The models of the SEDs of these PPNs are consistent with this, as dynamical timescales of 700–2000 years have been found in most cases for the ages of the densest region of the dust shells (Hrivnak et al. 2009, 2000, for $L = 8000 L_\odot$). These observed SEDs agree with the model SEDs determined from hydrodynamic, radiative transfer models of the evolution of the central star and the dust shell by Steffen et al. (1998) and Schönberner (2007). Among the timescales of these models are somewhat shorter, 500–700 years. Resolved dust shell modeling of IRAS 22272+5435 indicates a significantly shorter timescale of $\sim 380$ year (Ueta et al. 2001), although the analysis is somewhat complicated by the presence of the central star and the non-symmetric dust shell around it. In terms of the model of Blöcker (1995), IRAS 22272+5435 may be a case in which the star is still in the transition to the lower mass loss rate. A resolved dust shell model for the more evolved source IRAS 07134+1005 leads to a dynamical age of 1240 year (Meixner et al. 1987).
et al. 2004). While some of these observed PPNs do show a suggestion of some warm dust in their SEDs, which could be evidence for more recent, lower rate mass loss (Hrivnak et al. 2009), one of the cases, IRAS 05113+1347, has \( P = 133 \) days, again supporting the fact that the decline from the intensive mass loss begins at \( P > 100 \) days. An additional support for the longer initial evolution timescales is the fact that most of the 12 objects in this study have \( T_{\text{eff}} < 7000 \) K (9/12) rather than \( T_{\text{eff}} \geq 7000 \) K (3/12), suggesting a slow initial evolution, since there should not be an observational bias against detecting the hotter C-rich PPNs. There are four known additional hotter C-rich PPNs, IRAS 01005–7910 (B0e),\(^7\) IRAS 16594–4656 (B7e), and two recently discovered by Reymiers et al. (2007) with spectral types of A8 and A9 and \( T_{\text{eff}} \) of 7750 and 8000 K. Even including these does not change the result that a majority have cool central stars. This result suggests that the actual timescales to evolve to the central stars of PNs are significantly longer than determined in the Blöcker models in which evolution with extensive mass loss continues until the pulsation period \( P = 100 \) days and then decreases. However, the Blöcker (1995) model in which mass loss begins to decrease at \( P = 150 \) days (rather than \( 100 \) days) has a evolutionary timescale of \( \sim 7000 \) year for the PPN phase, from the end of the decreasing AGB mass loss to the beginning of the PN phase (in addition to the 2800 year from the peak to the end of the decreasing AGB mass loss rate). This is too long a value for the PPN phase and suggests that the post-AGB mass loss rate is higher than the Reimers rate assumed in the Blöcker study.

One would like to be able to empirically determine the evolution of \( P \) (and \( T_{\text{eff}} \)) with time for individual PPNs, as has been attempted for some RV Tauri variables (Percy et al. 1991). This would allow us to better constrain the models and the post-AGB mass loss rates. From the present study, one can use the observed relationship between period and temperature to show the average evolution of these two quantities. This is shown graphically in Figure 18. An approximately linear relationship can be seen over the limited temperature range of 5250–8000 K covered in this study. From the slope of this relationship, we can determine a rate of change in the pulsation period \( P \) with \( T_{\text{eff}} \) of \( \Delta P/\Delta T_{\text{eff}} = -0.047 \) days K\(^{-1}\). While the actual evolution in time of an individual PPN will depend upon \( M_{\text{core}} \) (and \( M_{\text{ZAMS}} \); see Blöcker 1995) and the level of ongoing post-AGB mass loss, this gives a general result. If we assume, for example, that these stars have completed the transition in mass loss from the high AGB rates and are now losing mass at the much lower Reimers rate, then we can couple this with one of the post-AGB evolution models to calculate the expected evolution in pulsation period. We will use the results of Steffen et al. (1998) following the end of the decreasing mass loss from the AGB to the Reimers rate. Although we showed above that timescales values from this model must be adjusted for the fact that the AGB rate appears to end earlier than assumed in the model, the model evolutionary rate should still be appropriate in the Reimers regime. As stated by Schönberner (1983), “the evolution depends on the current values of \( M \) and is independent of earlier mass loss phases, provided thermal equilibrium has not been destroyed.” Steffen et al. (1998) find, for a carbon-rich star with \( M_{\text{core}} = 0.605 M_\odot \), an evolution from \( T_{\text{eff}} \) of 6050 K to 8500 K occurs in 675 years, or a rate of 3.6 K yr\(^{-1}\). Combining this with our empirically determined average rate of change of pulsation period with \( T_{\text{eff}} \) results in a rate of change in period of \( \Delta P/\Delta t = -0.17 \) days yr\(^{-1}\) or a change of \( \Delta P = -2.4 \) days over the 14 year observing interval. Such a change should be measurable with sufficient observations over a long enough baseline. We found a tentative value for the rate of period change of this order for two of the best observed cases (Section 5.3). However, we caution that this is based on a relatively small temporal baseline and will need to be monitored for an additional decade or so before one can begin to feel confident in the results. Also, the results would be strengthened by the addition of more PPNs to the determination of the \( P-T_{\text{eff}} \) relationship. We are in the process of carrying out a similar light curve study of oxygen-rich PPNs. Note that Sasselov (1993) nicely outlined some of the general evolutionary aspects of pulsating post-AGB stars that are in good quantitative agreement with the results found in this study. When we examine the \( P-T_{\text{eff}} \) relationship on a logarithmic scale, we find a slope of \(-3.5 \pm 0.4\), within the range of \(-3.0 \) to \(-3.7\) listed by Sasselov and close to the theoretical value of \(-3.72\) based on the fundamental-mode pulsation in Miras (Ostlie & Cox 1986).

The peak-to-peak range of the light variation also shows a trend with period. The PPNs with the longest periods also have the largest light curve variations. Listed in Table 8 is the maximum seasonal variation in the \( V \) band of each PPN. In Figure 19, these maximum variations are seen to decrease approximately monotonically with decreasing period and with increasing effective temperature. This decrease in light curve variation with \( P \) and with \( T_{\text{eff}} \) is what one would expect to see as the atmosphere decreases in size while the star evolves at constant luminosity toward higher temperature. Note that these maximum seasonal variations are much larger than the amplitudes determined from the sine curve fitting to the long-term light curves; this is at least partly due to the multiple periods or varying amplitudes inherent in these pulsating stars. The comparison of the light variations with pulsation periods shows a marked transition at period values of \( \sim 120–130 \) days, below which the amplitudes are low and in the range 0.13–0.23 mag, while at longer periods they are larger, in the range of 0.5–0.7 mag. (IRAS 07430+1115 is the lone exception; it is

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7 We have observed IRAS 01005–7910 and found it to vary on a short timescale of less than a few days. None of the others have published light curve studies.
of radiative, nonlinear pulsation models of post-AGB stars with parameters in the following ranges: $M = 0.6–0.8 \ M_\odot$, $T_{\text{eff}} = 5600–6300 \ K$, and $L = 4500–8000 \ L_\odot$. These model parameters were chosen in part to fit the observed light and velocity curves of the PPN IRAS 07134+1005. The results of these studies are that the light curve periods and amplitudes decreased with increasing temperature and also decreased with increasing mass and decreasing metallicity. More model calculations, with the explicit inclusion of convection and producing larger periods, are needed to help interpret these new PPN light curves.

The observed maximum changes in $\Delta(V–R)$ attributable to temperature changes, excluding the changes associated with trends in the brightness, are listed in Table 8. These were transformed to changes in temperature based on the published temperatures and a color–temperature table of Cox (2000, Table 15.7). These $\Delta T_{\text{eff}}$ values range from $\sim 300–750 \ K$, with no correlation with $T_{\text{eff}}$. In some cases, such as IRAS Z02229+6208 and 07430+1115, these are likely lower limits since the $R$ observations were few in the early years. As noted earlier, the observed $(V–R)$ colors are reddened by the interstellar and particularly circumstellar dust, and thus the temperatures are derived from the spectroscopic analyses.

The observed long-term trends in the brightness of a few of the PPNs can most likely be ascribed to the effects of changes in the line-of-site circumstellar dust. IRAS 22223+4327 appears to get gradually fainter and IRAS 04296+3429 and AFGL 2688 appear to get gradually brighter. AFGL 2688 shows the largest change in brightness and gets measurably bluer as it gets brighter. IRAS 19500–1709 shows a rapid drop in brightness, during which time it gets redder, and then a gradual rise in brightness during which it gets bluer. This can be explained by the sudden formation and more gradual dissipation of a dust cloud or the passage of a circumstellar dust cloud with a more opaque leading edge.

7. SUMMARY AND CONCLUSIONS

In this study, we carried out a photometric $V$ and $R$ monitoring survey of 12 carbon-rich PPNs over an interval of 14 years. This is the first systematic, long-term (> 10 year) light curve study of a homogeneous group of PPNs. The targets were all of spectral type F and G. Below are the primary results of this study.

1. All of these PPNs varied in brightness and color, with the general result that they are redder when fainter.
2. Periods of the variations were found for all of the targets (except perhaps AFGL 2688). These range from $\sim 38$ to 153 days, with a maximum $V$ variation (peak-to-peak within a season) ranging from 0.13 to 0.67 mag. The objects with the later spectral types, mid- to late-G, have the longer periods and the larger variations.
3. The objects show evidence for multiple periods and/or changing periods and/or changing amplitudes. Two of them have light curves that suggest a longer beat period (IRAS 22272+5435 and 22223+4327) and two of them have light curves with a suggestion of intervals of alternating deeper and shallower minimum (IRAS 20000+3239 and Z02229+6208). Nevertheless, all except the two with the shortest periods (IRAS 07134+1005 and 19500–1709) show a clearly dominant period in the data set. These results are consistent with the variation being due to pulsation and not binary interactions.
4. An approximately linear correlation was found between the period of variation and the effective temperature over the
temperature range observed in this study (5250–8000 K), with the shorter periods associated with higher temperatures. The range of light variation is also seen to decrease approximately monotonically with temperature.

5. The presence of pulsation periods as long as 150 days in PPNs with detached shells implies that the intensive AGB mass loss had ended before the period had decreased to 150 days. This has significant implications for modeling post-AGB evolution rates, since the rates depend upon the level of post-AGB mass loss. Since some post-AGB evolution codes tie the pulsation period to a mass loss prescription (i.e., Blöcker) that assumes that intensive mass loss has ended by the time that the pulsation period has reduced to 100 days, these models will need to be revised. This would have the result of significantly increasing the initial stages of post-AGB evolution.

6. An average rate of change of the pulsation period with time can be determined by combining the empirically determined rate of variation of period with temperature and the model-dependent rate of change of temperature with time. These lead to an approximate rate of period change of −0.2 days yr⁻¹, a rate that is potentially detectable within a few decades. Our observations of individual PPNs over this 14 year interval are complicated by the evidence for multiple periods, but give some tentative results that are not inconsistent with this value.

As can be seen, the study of the light curves of PPNs and the determination of their periods has the potential to constrain the models of post-AGB stellar evolution and to reveal evolution in real time. In addition, these light curves together with radial velocity curves, when compared with appropriate pulsation models, have the potential to determine fundamental properties of the stars, such as mass and luminosity. These will be explored further in subsequent papers. We are continuing to monitor the light curves of many of these PPNs to extend the time baseline.

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