Evaluating the Pan-STARRS Variability Parameter

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By Thursday (4/18) we need: well thought out section titles and plots that show all the points we wanna make

remake prob(f) plot with all 300,000 stars (not only 80,000)

LS analysis on ATLAS Pathfinder Telescope data, verified PS variability criteria

1. INTRODUCTION

- why we care
- what made us care about this project
- NO structure / distance stuff (maybe put it in looking forward section at end)
- talk about PS catalog
- variability surveys (discuss other attempts to measure variables across the sky)
- why are variables interesting
- why do we want to find variables and care about where they are located
- Summary: we ran LS, analyzed stars, why did we do it all
- Mention what will be discussed: "in section 2 we describe the observations we used..."

2. ATLAS PATHFINDER 1 OBSERVATIONS

- we used data from ATLAS
- supplemented with ATLAS data [REF TONRY] (possibly make this s subsection)
- what was the weather like during observations
- PSF FWHM variations (only include if we discuss crowding)
- 'we recieved the reduced image data from the ATLAS pipeline; which gave us RA, Dec, mag, etc...'
- `http://fallingstar.com/how_atlas_works.php`

[VERIFY CORRECT CITATIONS:
Initially, determination of variability was going to be achieved using data collected by the *griProject*[1]. The *griProject* is [EXPLAIN]... In order to reduce aliasing, extra observations needed to be made. Observation procedures are discussed in § 2 2.2. [PATHFINDER USED FOR GRI DATA...the reduction process is discussed at length Tonry in...cite]
We received the reduced image data from the ATLAS pipeline[2][3]

2.1. SNR Calculation

To calculate an appropriate sampling frequency and SNR, typical RR Lyrae light curves[4] were used with artificially introduced gaps and noise following the Gaussian distribution. To determine distances from the PL relations[5] within $\simeq 5\%$ accuracy assuming typical metalicity $Z = 0.001$, we need periods within $\simeq 1\%$ accuracy. By using the Lomb-Scargle analysis (discussed in section 4), it was found that 15 nights with 10 observations/night is the lower limit sampling rate to achieve the period accuracy. Since the magnitude fluctuations of RR Lyrae are typically in the range of 0.3 to 2.0 mags[6], the uncertainty in magnitude was taken to be 0.1 mags, and the changes, 0.01 to 0.1 mags, in the uncertainty did not affect the period determinations significantly. Thus we only needed 10% photometry. For $m_g = m_r = 16$ and $m_i = 15.7$, an exposure time of 20 sec yields 10% photometry for the ATLAS pathfinder telescope.

2.2. Data

Is it $b^{II} = +5°$ or $b = +5°$??
[NEED TO DEFINE FOV]
[VERIFY RA DEC RANGE (NOT WHAT WAS PUT INTO SIMBAD)]
[NEED TO CITE TONRY FOR OUR OBSERVATIONS]
[MENTION THAT OUR OBS NECESSARY TO REDUCE ALIASING]

Using the Pathfinder telescope, observations were made at two galactic latitudes ($b^{II} = \pm 5°$) and spanned a range of galactic longitudes ($202° < l^{II} <$

232°). Exposures were collected for 20 s and separated by 3° longitudinally. For implementation by the Pathfinder telescope, a conversion to RA and Dec was made; giving a range of $93 < RA < 119°$ and $-20° < Dec < 13°$, as shown by Figure 9. To account for the 0.05 ° gap between the detectors, a 0.1 ° offset in RA was implemented on every other night. Spanning 20 nights, 10 observations a night were collected on 3/8/16-3/27/16. Luckily all of these nights had weather perfectly attuned for observations. Half a night of observations were lost on 3/19/26, due to a crash of the server controlling the telescope.

[dRA = dangle / cos(Dec)]
[EXPLAINS EXACT OBSERVATIONAL PLAN...NECESSARY?]
Observations were traced out by moving the FOV by 3° longitudinally, starting at $b^{II} = -5°$, $l^{II} = 202°$ and ending at $b^{II} = -5°$, $l^{II} = 232°$. Once observations at $b^{II} = -5°$ were complete, the FOV was shifted to $b^{II} = +5°$, $l^{II} = 232°$.

3. CONSTRUCTING STELLAR LIGHT CURVES

- how we selected stars (12+ obs, 1x1 deg^2, etc)

The selection process began

4. PERIODOGRAM ANALYSIS

[INTRO TO WHAT IS PERIODOGRAM...WE CONSTRUCT PERGRAMS USING LS METHOD]

- extract variability from LS
- describe how it works and why we used LS
- major aliasing at 1 day and 0.5 day periods
- things that fall at at -50 (in Figure ??) means that those are VERY probably variable stars
- roughly ____ stars fell at -50 in Figure ??
- 315,992 stars tested for variability
- other stars (outside of 315,992) are statistically unlikely to be variable
- brief explanation of the fast LS
- period search range to avoid aliasing
- compute gri periods individually and compare each other. if period differences are less than 0.04 days, next step

To extract periods from light curves, the Fast Fourier Transform (FFT) is usually used. For our data, however, FFT is not optimal due to the data gaps. To deal with the data gaps, the Fast Lomb-Scargle (FLS) periodogram analysis[7 8] was used in this study because of its high computational efficiency. FLS extracts not only periods but also the significance levels of periods in the form of $\log Pr(rnd)$. The more negative the significance levels are, the more significance the periods are. The outputs of FLS is shown in FIG. 2. Since our observational period is roughly a day, there are major aliasings at the periods with integer multiple of a day. To avoid the aliasing, we masked a period range with high significance level and used the masked range for further analyses.

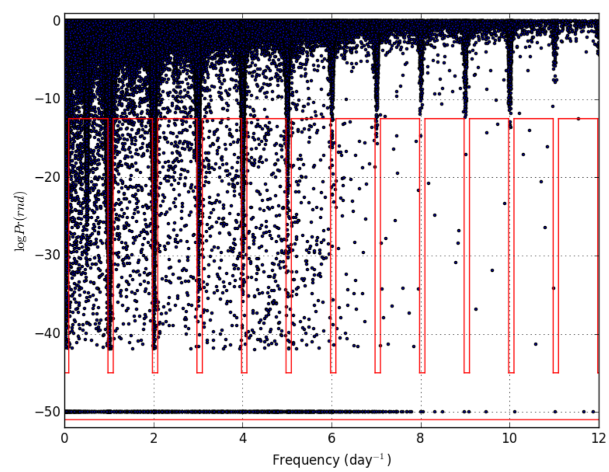


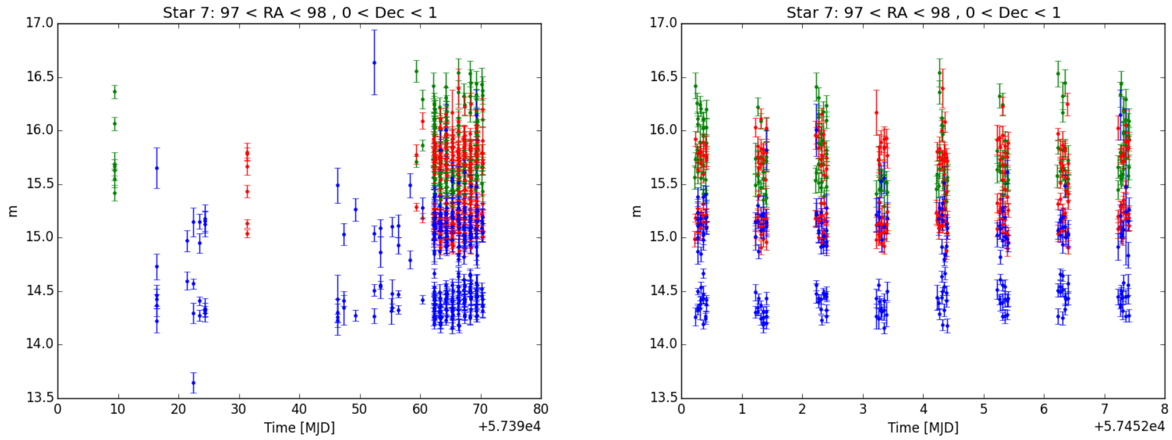
FIG. 2: $\log Pr(rnd)$ *vs frequency (day^{-1}) of* 315,992 *stars selected by the quartile criteria. The red lines define the masked regions with high significance level (*$\log Pr(rnd) < -12.5$*) and no aliasing (*$0.02 <$ *frequency* < 0.98*,* $1.02 <$ *frequency* < 1.98*, etc.). The masked region contains* 5,658 *stars.*

5. RR LYRAE SELECTION CRITERIA

- Fourier series fit to extract variable types
- compute FS and calculate χ^2/ndf. if $\chi^2/ndf < 10$, next step.
- find abs(max/min(FS)). if abs(max/min(FS)) > 0.2, then we call it's a variable stars.
- explanation of period error estimation using Fourier series.

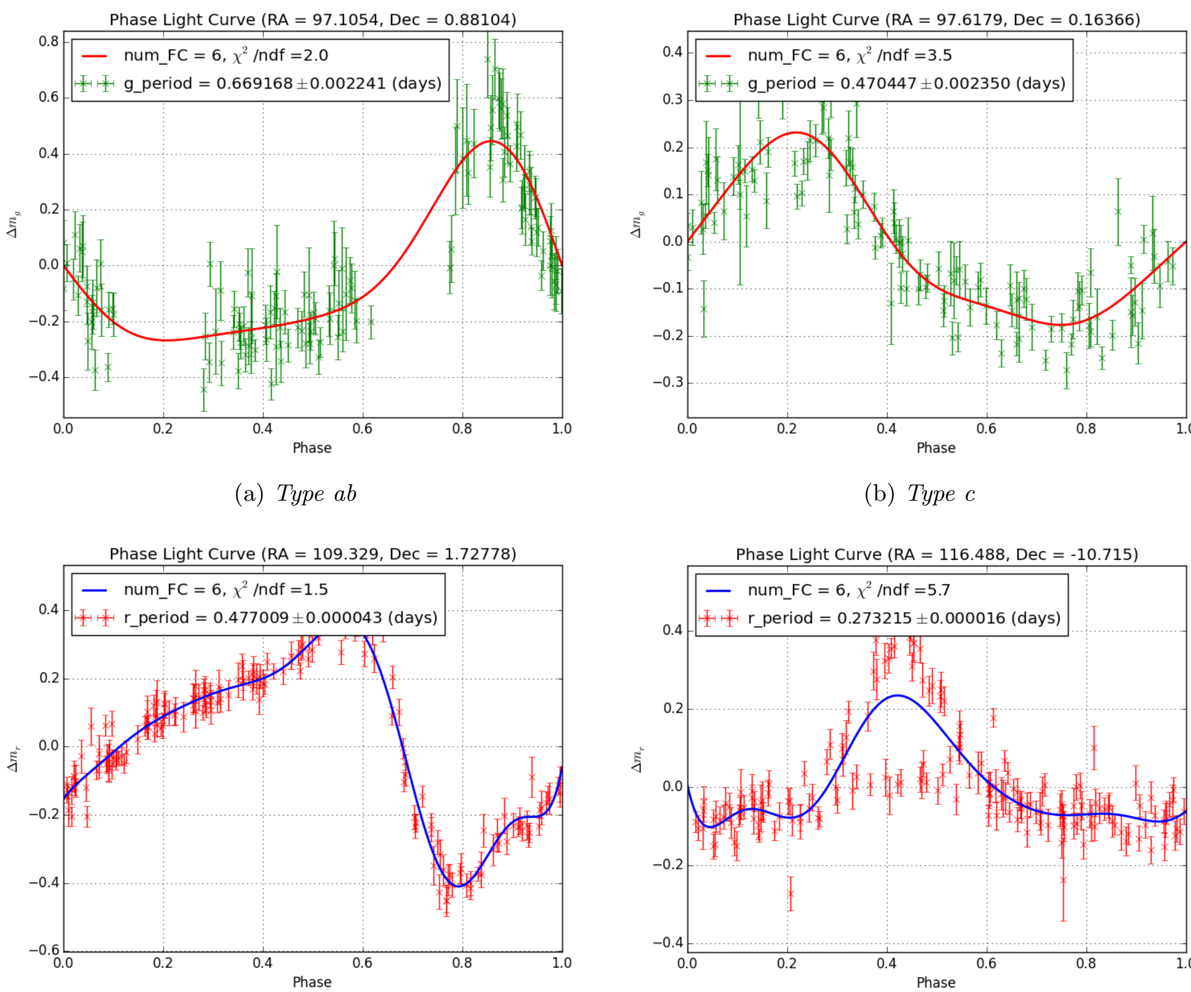
6. RESULTS

- compare with PS[9]



(a) (b)

FIG. 1: *Light Curve of a variable star. Panel '(a)' shows a light curve constructed using all collected and ATLAS data. Panel '(b)' is a restricted selection of '(a)', not showing any observations made by ATLAS.*



(a) *Type ab*

(b) *Type c*

(c) *Blazhko Modulated*[4]

(d) *Period Doubling*

FIG. 3: *Four major types of RR Lyrae stars found in this study.*

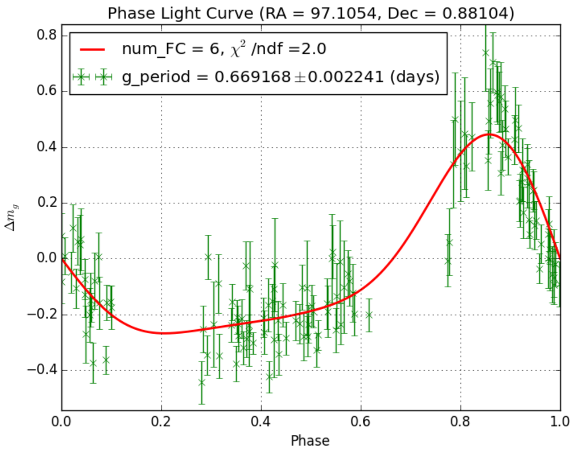


FIG. 4: *Type ab*

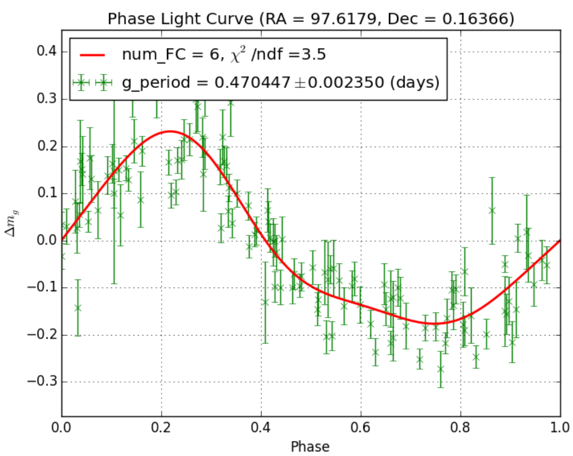


FIG. 5: *Type c*

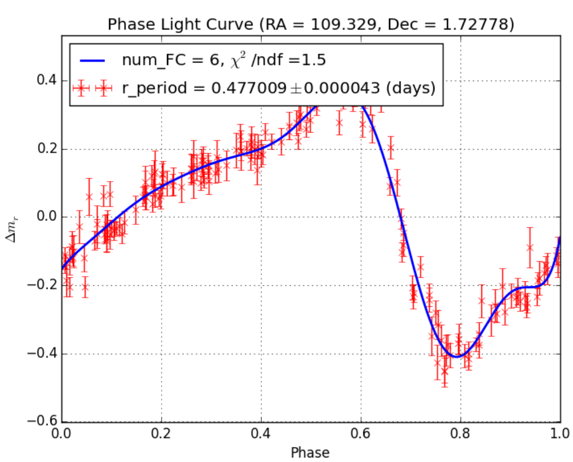


FIG. 6: *Type ?*

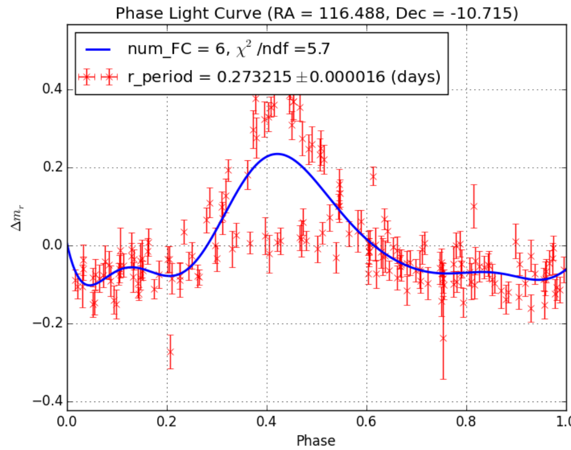


FIG. 7: *Blazhko Effect (period doubling)*

- density/distribution of variables in sky
- (what LS gave us for our catalog)
- put a table with 5 stars, to show off part of catalog

6.1. Spatial Distribution

Figure 8 shows no correlation between the HPS criteria and verified RR Lyraes. Of the 1.5 Billion stars identified in our FOV, we isolated the 320,000 most variable using
[DESCRIBE LOWER QUARTILE METHOD]
[DESCRIBE logPr(rnd)...how some vars might have slipped past, but only]
[CITE WHERE IT SAYS RRLYRAE HAVE 0.5 ¡ PERIOD ¡ 1.2 [DAYS]]
A grouping and matching algorithm, written by J. Tonry[1], made it possible to isolate and group stars from various nights of observations. Implementation of logPr(rnd) allowed for 100% of RR Lyrae verification. Only stars with different variable classifications, those having lower amplitude variations, would have been able to go undetected. Masking out regions of high aliasing reduced the need to run LS and verify variability, due to the statistically improbability of these sources being variable. A total of 5,658 stars fell within the masked region, shown in Figure **??**. LS analysis identified 1,239 variable stars in our FOV. A defining characteristic of RR Lyrae is their variability periods, falling between 0.5 and 1.2 days. Using this restriction 279 stars were confirmed to be RR Lyrae. Variability classification was confirmed by visually inspecting the light curves of all 279 RR Lyrae and the remaining 960 unclassified variable stars. Following this procedure gives us 100% purity.

HPS $\rho_{RRLyrae}$	HPS_{total}	$HPS_{matched}$	RR	var (notRR)	$Not-Variable_{matched}$	$notvar_{notmatched}$(outside mask)	Prob(var)	Prob(RF
0.0-0.05	5029	138	9	37	92	4891	46/138 = 0.33	9/138 = 0
0.05-0.1	124	25	1	11	13	99	12/25	1/25
0.1-0.2	154	38	1	18	19	116	19/38	1/38
0.2-0.3	116	36	1	14	21	80	15/36	1/36
0.3-0.4	82	36	1	21	14	46	22/36	1/36
0.4-0.5	85	34	1	19	14	51	20/34	1/34
0.5-0.6	90	41	5	17	19	49	19/41	5/41
0.6-0.7	89	47	6	22	19	42	28/47	6/47
0.7-0.8	64	39	5	23	11	25	28/39	5/39
0.8-0.9	46	28	4	19	5	18	23/28	4/28
0.9-1.0	21	15	1	8	6	6	9/15	1/15
0.0-1.0	5900	477	35	209	233	5423		

TABLE I: A comparison of observations to HPS RR Lyrae candidates.

Using the same matching algorithm[1] made comparing observations with other variable catalogs possible. To evaluate the HPS RR Lyrae criteria, our observations were matched to stars flagged as potential RR Lyrae candidates by HPS. Shown in Table I and Figure 8, there is no correlation between HPS criteria and verified RR Lyrae stars.

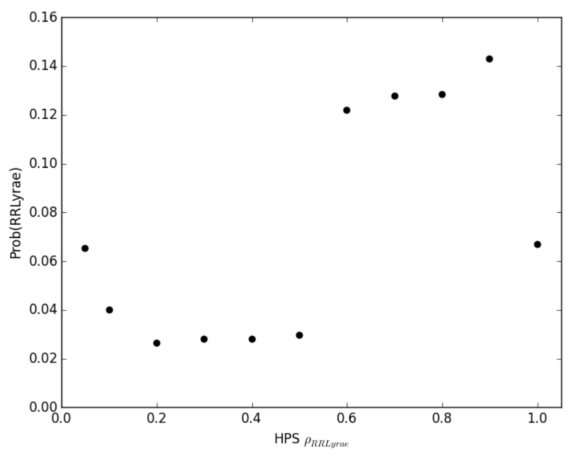


FIG. 8: *Evaluation of HPS RR Lyrae criteria.*

6.2. Simbad Completeness

- Pull established RR list from Simbad
- Pull other variable data from simbad, too
- Compare list of observed RR to catalogs
- Is anyone actually reading this outline, this bullet point serves no purpose
- Wow, its sad how little Jeff did since class began (especially after JT gave him the code to do it a month ago) - 6 obs x 4 nights = January-April work period haha
- Establish completeness with Simbad

[FIX SIMBAD CITATION]
In order to evaluate the completeness of our results, comparisons needed to be made to other variable star catalogs. Simbad[10] provided a list of variable stars within our FOV. Pulsating sources encompasses all variable objects.
[OF THESE WE MATCHED...RR LYRAE...REF FIGURE]

[review what he did, but heres a summary:]
[48 simbad objects overlay our FOV]
[33 have an entry in lsum.dat]
[Of 15 that overlap w/o lsum entry]
[14 are defective]
[at least one filter has less than 10 detections]
[=¿ it's a survey problem, not an LC problem]
[P(rand) for the 33 that do occur in lsum]
[27/33 show up as high probability variables]

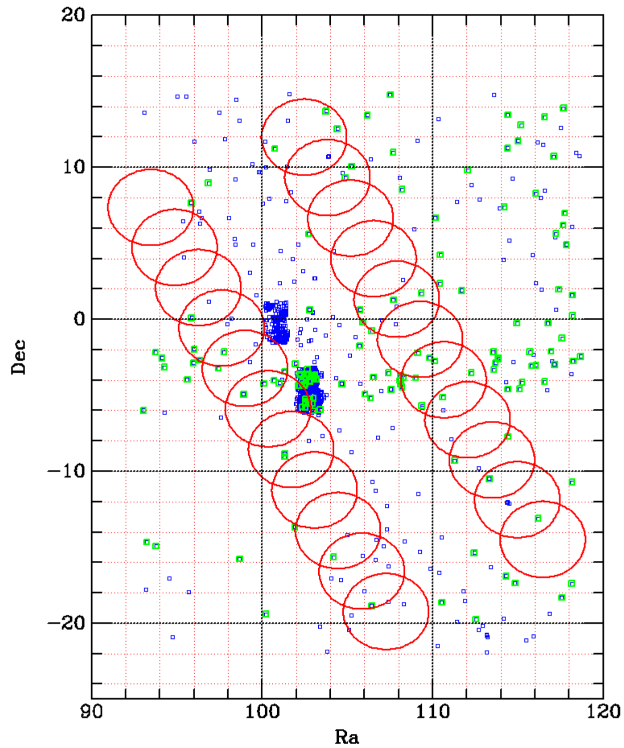


FIG. 9: *Observation path with Simbad pulsators in blue and RR Lyrae in green.*

7. DISCUSSION

- Evaluation of PS criteria
- what went wrong
- what could have gone better
- future outlook
- we could map spiral arms using x y and z

8. SUMMARY AND CONCLUSIONS

[TALK ABOUT IT]

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