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)

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

1. INTRODUCTION

Hello DH[1]

- 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 FLS, 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*[2].
The *griProject* is [EXPLAIN]...
In order to reduce aliasing, extra observations needed to be made. Observation procedures are discussed in § 2 2.1. [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[23]

2.1. Data Collection

[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 ($202° < l^{II} < 232°$). Observations discussed here indicated the center of each FOV. 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 5. 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.

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 $b^{II} = +5°$, $l^{II} = 232°$.

2.2. Object Cuts

Various data points, reduced by the ATLAS pipeline[2], were returned with magnitude errors of zero. Such values were not used determining variability of the source. In order for an identified star to be considered for variability testing, we required a minimum of 12 "good" observations. A "good" detection is meets the minimum PSF, does not fall on the edge of each 1 deg^2 FOV, and was observed with clear skies. A minimum of 12 observations was deemed necessary, in order to eliminate aliasing, as discussed in **??**. After observation cuts were applied, 1.5 Billion stars remained in our FOV.

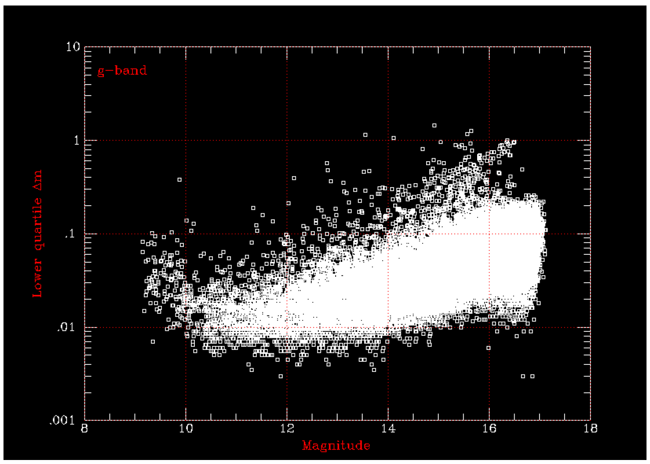


FIG. 1: *Lower quartile variance as a function of magnitude.*

In order to exploit the lower quartile variance, shown in Figure **??**, a factor of $0.2m$ was added to account for Poisson error. The higher a star deviates from the average value, the more likely it is variable. This flagged 320,000, of the observed 1.5 Billion, for further variability verification.

As a result of running FLS, the most variable candidates fell below $logPr(rnd) \leq -45$, shown in Figure **??**. An in depth discussion how $logPr(rnd)$ works can be found in *Numerical Recipes*[?][?]. Using $logPr(rnd)$ made it impossible to miss any variable star with $0.05 \leq Period \leq 1.2$[?]. It is statistically improbable that any observed variable star wasn't flagged. If any variable stars were not identified, they must have lower period variations and are therefore not classified as RR Lyrae.

3. CONSTRUCTING STELLAR LIGHT CURVES

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

The selection process began

4. EVALUATING THE HPS VARIABILITY PARAMETER

A paper, *Finding, Characterizing and Classifying Variable Sources in Multi-Epoch Sky Surveys: QSOs and RR Lyrae in PS1 3π Data*[4] (HPS), quantifies the likelihood that a star is an RR Lyrae. Using their variability statistic, $\rho_{RRLyrae}$, density and distribution of RR Lyrae and other variable candidates were determined. Table I evaluates the validity of HPS's variability criteria.

Figure 3 shows no correlation between the HPS criteria and candidates verified to be RR Lyrae stars. Of the 1.5 Billion stars identified in our FOV, we isolated the 320,000 most variable, as described in § 2 2.2. Determination of variability class for these objects in discussed in **??**.

A grouping and matching algorithm, written by J. Tonry[2], made it possible to isolate and group stars from various nights of observations. Implementation of logPr(rnd) allowed for complete confirmation of RR Lyrae candidates. 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 a more rigorous analysis, due to the statistically improbability of these sources being variable. A total of 5,658 stars fell within the masked region, shown in Figure **??**. FLS and FSS analysis identified 1,239 variable stars in our FOV. A defining characteristic of RR Lyrae is their variability periods, falling between 0.05 and 1.2 days. Using this restriction, 244 confirmed to be RR Lyrae matched the HPS dataset. Variability classification was confirmed by visually inspecting the light curves of all 244 RR Lyrae candidates as well as the remaining 995 unclassified variable stars. Following this procedure gives us 100% purity.

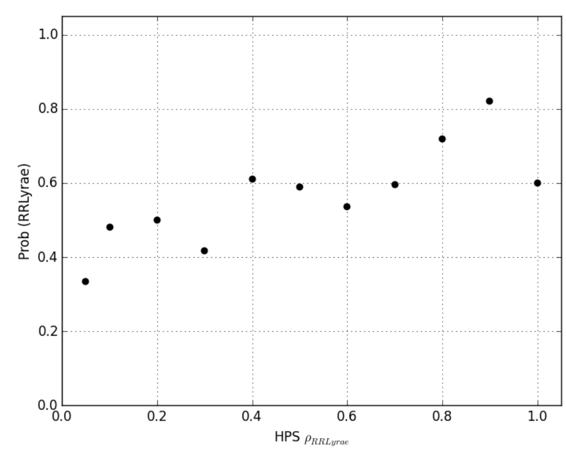
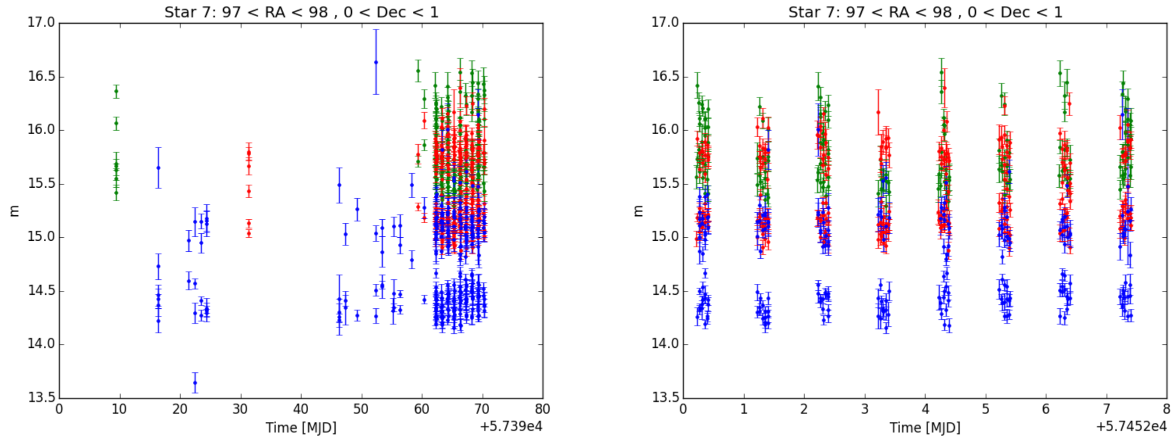


FIG. 3: *Evaluation of HPS RR Lyrae criteria, using matched RR Lyrae.*



(a) (b)

FIG. 2: *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.*

HPS $\rho_{RRLyrae}$	HPS_{total}	$HPS_{matched}$	RR Lyrae	Not RR Lyrae	Prob(RR)	Prob(notRR)
0.0-0.05	5029	138	46	92	0.33	–
0.05-0.1	124	25	12	13	0.48	–
0.1-0.2	154	38	19	19	0.50	–
0.2-0.3	116	36	15	21	0.42	–
0.3-0.4	82	36	22	14	0.61	–
0.4-0.5	85	34	20	14	0.59	–
0.5-0.6	90	41	22	19	0.54	–
0.6-0.7	89	47	28	19	0.60	–
0.7-0.8	64	39	28	11	0.72	–
0.8-0.9	46	28	23	5	0.82	–
0.9-1.0	21	15	9	6	0.60	–
0.0-1.0	5900	477	244	233	0.51	–

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

The same matching algorithm[2] made comparing observations with other variable catalogs possible. To evaluate the HPS RR Lyrae criteria, our observations were matched to stars analyzed for variability, by HPS. Shown in Table I and Figure 3, there is no correlation between HPS criteria and verified RR Lyrae stars. HPS claims any star with an assigned $\rho_{RRLyrae} > 0.20$, is most likely an RR Lyrae. Furthermore, if $\rho_{RRLyrae} > 0.05$, the candidate is definitively an RR Lyrae. Figure 3 shows the fractional portion of observed RR Lyrae, that matched to stars that have been assigned $\rho_{RRLyrae}$, by HPS. There is a distinct correlation between confirmed RR Lyrae and assigned $\rho_{RRLyrae}$ values. However, over 16% of all observed RR Lyrae, that matched to HPS stars, have $\rho_{RRLyrae} < 0.20$. Similarly, 10% of all matched RR Lyrae fall below $\rho_{RRLyrae} < 0.05$. Of all 244 matched RR Lyrae, only 9 have the highest RR Lyrae probability assigned, $\rho_{RRLyrae} > 0.90$.

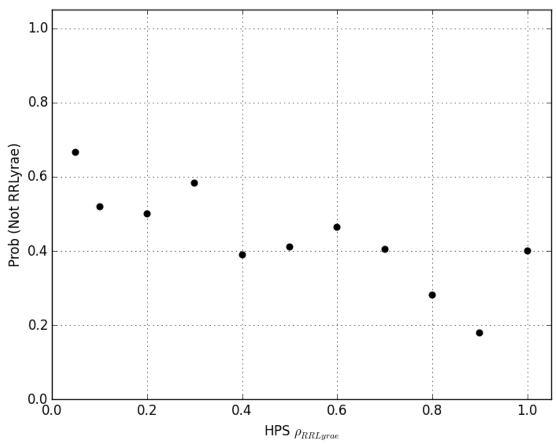


FIG. 4: *Evaluation of HPS RR Lyrae criteria, using non-RR Lyrae matched objects.*

Shown in Figure 4, there exists an inverse relationship, between non-RR Lyrae confirmed stars and HPS assigned $\rho_{RRLyrae}$. All stars confirmed as not begin RR Lyrae should have assigned $\rho_{RRLyrae} > 0.20$, according to HPS; yet 23% of all matched stars do not meet this criteria. Complete validity of HPS's $\rho_{RRLyrae}$ would be indicated by 0 verified, non-RR Lyrae stars, being matched with a $\rho_{RRLyrae} > 0.05$. This is not the case, with 30% of all matched stars begin confirmed non-RR Lyrae and having an assigned $\rho_{RRLyrae} > 0.05$. While HPS's $\rho_{RRLyrae}$ may indicate if a star is an RR Lyrae, it is not sufficient for absolute determination.

5. DISCUSSION

In order to evaluate the completeness of our results, comparisons needed to be made to other variable star catalogs. Simbad[5] provided a list of variable stars within our FOV. Pulsating sources encompasses all variable objects. With 48 objects overlapping our FOV, shown in Figure 5, we achieved a completeness of 98%.

[possible put two light curves in as examples of objects that overlap our field]

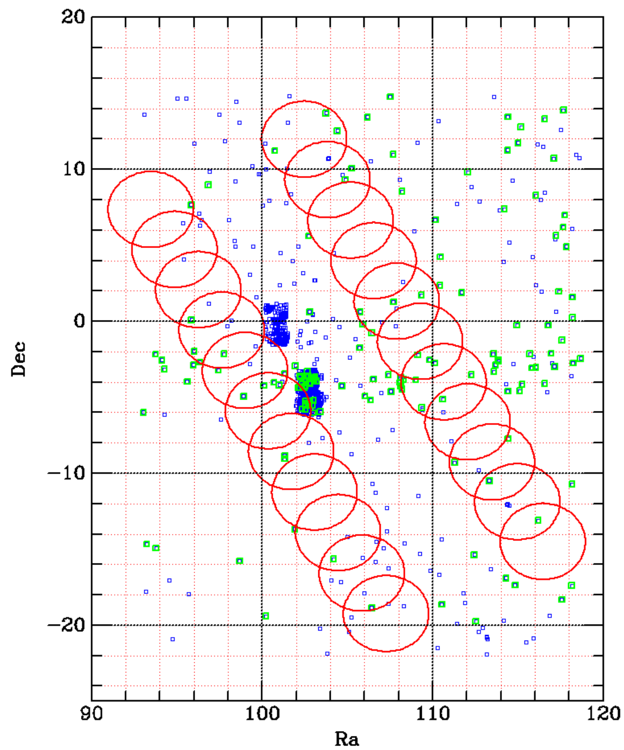


FIG. 5: *Observation path shown in red, with Simbad pulsators in blue and RR Lyrae in green.*

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