Pan-STARRS 1 as a $3\pi$ Time Domain Sky Survey

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Pan-STARRS 1 as a Time Domain Survey

most ambitious panoptic multi-epoch multi-band survey to date:

- solar system objects
- transients
- proper motions (& parallaxes)
- variable sources
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QSOs

- intrinsically interesting, and astrometric reference points
- varying on weeks to year time-scales

RR Lyrae:

- precision 3D mapping of the (old) Milky Way
- varying on 1/4 day timescales

panoramic: surveyed 3/4 of the sky (DEC > -30 deg) in 5 bands

**rapid**: time-domain survey
- \(\sim 60\) epochs over 3 years
- 5 bands (grizy)
- non-simultaneous
PS1 as a Time-Domain Survey

PS1 $3\pi$ interesting because of its size $\Rightarrow$ "all-sky" time domain astronomy

how to characterize variability statistically?

forget about simple single-band models!
PS1 as a Time-Domain Survey

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how to characterize variability statistically?

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⇒ solution: model non-simultaneous multi-band variability
PS1 as a Time-Domain Survey

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how to characterize variability statistically?

forget about simple single-band models!

$\Rightarrow$ solution: model non-simultaneous multi-band variability

$\Rightarrow$ generic: other variables ($15\text{ min} < \text{time scale} < 4\text{ years}$)
Which sources vary at all?

multi-band $\chi^2$ statistics for PS1 photometry, assuming non-varying sources

classification: SDSS S82
Characterize Light Curves

multi-band structure-function variability model $L(\text{grizy} | \omega_r, \tau)$: how much should you expect a source to vary within $\Delta t$?

$$V(|\Delta t|) \equiv \mathbb{E}[\left(m(t) - m(t + \Delta t)\right)^2]$$

assume functional form

$$V(\Delta t) \overset{\text{model}}{=} \omega_i(\lambda_i) \omega_j(\lambda_j) \left(1 - \exp\left[-\frac{|\Delta t|}{\tau}\right]\right)$$

with

$$\tilde{m}_\lambda(t) = m_\lambda(t) - \bar{m}_\lambda, \omega_k(\lambda_k) = \omega_r \left(\frac{\lambda_k}{\lambda_r}\right)^\alpha$$

$\Rightarrow$ fit amplitude $\omega_\lambda$, variability time-scale $\tau$ & $\bar{m}_\lambda$

$\Rightarrow$ characteristic variability timescale & amplitude
**Characterize Light Curves**

multi-band structure-function variability model $\mathcal{L}(grizy|\omega, \tau)$:
how much should you expect a source to vary within $\Delta t$?

$\Rightarrow$ fit $(\omega_\lambda, \tau) \& \bar{m}_\lambda$

$\Rightarrow$ characteristic variability timescale & amplitude
Characterize Light Curves

multi-band structure-function variability model $\mathcal{L}(grizy | \omega_r, \tau)$: how much should you expect a source to vary within $\Delta t$?

⇒ fit $(\omega_\lambda, \tau)$ & $\bar{m}_\lambda$
⇒ characteristic variability timescale & amplitude

RR Lyrae, $\omega_r=0.3$, $\tau=1.5$ days
QSO, $\omega_r=0.13$, $\tau=560$ days
Multi-Band Structure Functions

time-scale variability

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Classifying Variable Objects

How much can variation parameters & mean photometry (also from SDSS and WISE) tell us about classifications?

parameters $\Rightarrow$ classification probabilities
Parameter Space

- QSO
- RR Lyrae
- other

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Classifying Variable Objects

How much can variation parameters & mean photometry (also from SDSS and WISE) tell us about classifications?

parameters $\Rightarrow$ classification probabilities

e.g.

- kernel density estimator (or extreme deconvolution) + importance sampling
- Random Forest Classifier (RFC)
Classifying Variable Objects

How much can variation parameters & mean photometry (also from SDSS and WISE) tell us about classifications?

parameters $\Rightarrow$ classification probabilities

Approach:

- use SDSS Stripe 82 classification in overlapping area as ground truth
- train Random Forest Classifier in Stripe 82, apply to PS1

SDSS S82:

- $\sim 60$ epochs simultaneous $ugriz$
- complete QSO and RR Lyrae classification
Classifying Variable Sources with PS1 \( 3\pi \) Data

How well does this classification work? We ”know” the answer in SDSS S82.

RR Lyrae

QSO

completeness: \# selected true RR Lyrae / \# true RR Lyrae (or QSO)

purity: \# selected true RR Lyrae / \# all selected sources (or QSO)
RR Lyrae Candidates

⇒ plausible number densities, plausible area distributions (Sagittarius stream)
Period Fitting of RR Lyrae Candidates

multi-band lightcurve templates derived from Stripe 82 (Sesar et al [2010])

period-folded PS1 photometry, using best-fitting lightcurve template (fit for period and distance)

- period fitting improves to 90% purity, 70% completeness in S82
- recover periods to 1 sec. & measure distance within 5%
Draco dSph galaxy: an example

all PS1 stars with $18 < r < 21.5$
Draco dSph galaxy: an example

RR Lyrae candidates selected using $p_{RR\text{Lyrae}} > 0.05$ ($\sim 90\%$ completeness and $70\%$ purity)
Draco dSph galaxy: an example

RR Lyrae candidates selected using $p_{\text{RRLyrae}} > 0.05$ (≈ 90% completeness and 70% purity), passing period fitting, using light curve models from S82 (Sesar et al. [2010]) (≈ 70% completeness and 90% purity)
Draco dSph galaxy: an example

RR Lyrae candidates selected using $p_{\text{RRLyrae}} > 0.05$ ($\sim 90\%$ completeness and $70\%$ purity), passing period fitting, using light curve models from S82 (Sesar et al. [2010]) ($\sim 70\%$ completeness and $90\%$ purity) $\Rightarrow \sim 80$ kpc away
**QSO Candidates**

**distribution of $p_{QSO}$ vs. (l,b)**

- QSO candidates ($0.6 < p < 1$)
- $E(B-V) = 1..2$

around Galactic anticentre

around Galactic northpole

- QSO: in S82, 85% purity, 85% completeness for $p_{QSO} > 0.5$
- plausible number densities, plausible area distributions:
- $\sim$ const. area density for QSO candidates ($\sim 20/\text{deg}^2$)

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Prospects

QSO candidates ⇒ set of QSOs for calibration and astrophysics

RR Lyrae candidates ⇒ maps of RR Lyrae halo stars to > 100 kpc

catalog of variable sources in general
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Take home message

using astrostatistical methods, even PS1’s sparse light curves can lead to (surprisingly) good variable classification