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FIRST FINDINGS ON COMETARY ACTIVITY FROM THE PTF COMET SAMPLE

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RESUMEN

Utilizamos la muestra uniforme Palomar Transient Factory (PTF) de cometas de período corto (SPC) y cometas de período largo (LPC) capturados entre septiembre de 2009 y marzo de 2013, para estudiar su dinámica y propiedades físicas en relación con su actividad para una mejor comprensión del cometa evolución. Esta campaña de observación fue parte de PTF en su fase intermedia (iPTF) en el Instituto de Tecnología de California (Caltech). La muestra fotométrica comprende más de 200 cometas, lo que la convierte en una de las muestras más grandes estudiadas hasta la fecha. Presentamos un nuevo enfoque para identificar cometas activos comparando las magnitudes anulares de los cometas con respecto a la distribución de estrellas de brillo similar dentro de la misma imagen. En este artículo, presentamos preliminares hallazgos sobre la actividad cometaria en relación con distancias al perihelio. Mostramos diferencias entre las distribuciones de los SPC y la de los LPC. En particular, como se esperaba, una fracción mayor de los LPC se encuentran activos a mayores perihelios que para los SPC. Nos fijamos en las proporciones de cometas activos en diferentes grupos de perihelios y los hemos comparado con trabajos y resultados anteriores. Mediante el estudio sus propiedades dinámicas y físicas en relación con su actividad y contrastando las diferentes poblaciones, es posible comprender mejor la evolución de los cometas, y por lo tanto la formación de nuestro sistema solar.

ABSTRACT

We present preliminary results from the Palomar Transient Factory (PTF) uniform sample of short period comets (SPCs) and long period comets (LPCs), captured between September 2009 and March 2013. We study their dynamical and physical properties in relation to their activity for a better understanding of cometary evolution. This observing campaign was part of PTF in its intermediate phase (iPTF) at the California Institute of Technology (Caltech). The photometric sample comprises more than 180 comets, which makes it one of the largest samples studied to-date. We present a new approach to identifying active comets that compares subtracted aperture magnitudes of comets with the distribution of stars of similar brightness in each image. In this paper, we present initial findings on cometary activity in relationship to their perihelion distances. We show differences between the distributions of the SPCs and that of the LPCs. As others predicted, it seems that a larger fraction of LPCs are found to be active at larger perihelia than for the SPCs. We look at ratios of active comets in different perihelia brackets and compare those to previous works and results. We do not discuss the statistical significance of our findings as this is still work in progress.

Key Words: comets: general — surveys

1. INTRODUCTION

To fully understand the history of our solar system, it is important to better understand comet formation and evolution and to study the different comet populations (A'Hearn et al., 1995, 2017). Short period comets (SPCs) are thought to come to the inner Solar System from the scattered disk of objects in the trans-Neptunian region (e.g. Duncan et al., 2004; Fernández et al., 2013), while long period comets (LPCs) are believed to be our only observational clues to the composition of the Oort Cloud, the outermost part of the solar system (e.g. Francis et al., 2005; Bauer et al., 2017).

Photometric surveys of large comet samples are made possible by a new generation of synoptic survey projects in astronomy. The different comet groups are expected to be related; dynamical models of planetary migration predict that these signatures are imprinted on the numbers, distribution, orbits, and

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physical properties of these objects (e.g. Snodgrass et al., 2011). By understanding the physical and dynamical properties of both populations of our solar system's small bodies, we can learn more about their origins, evolution, and fate. Studying the activity in different comet groups can improve our ability to separate primordial differences from evolutionary differences, allowing us to use the comets as tracers of the chemical and physical conditions in the early solar system (e.g., Lamy et al., 2004; Meech et al., 2004; A'Hearn et al., 2012; Mandt et al., 2015; Eistrup et al., 2019; Rubin et al., Rubin et al. (2019)). Our goal is to use the Palomar Transient Factory (PTF) uniform sample of SPCs and LPCs, to study their dynamical and physical properties in relation to their activity for a better understanding of cometary evolution.

We use data processed through the iPTF photometric pipeline (Laher al., 2014) hosted at the Infrared Processing and Analysis Center (IPAC) at CalTech, which yields accurate relative photometry and small systematic errors. While the above surveys were optimized for the study of small solar system objects, this study is complementary in that it will represent a systematic investigation of (1) a relatively large sample of comets using a single instrument with very uniform, high-precision data reduction and calibration tools resulting in low systematic uncertainties, (2) a sample encompassing different comet groups and subgroups including SPCs & LPCs, (3) a sensitivity (20.5 mag in the R-band)- competitive with recent published work in the visible domain, and (4) very importantly, a significant time coverage from Sep. 2009 to March 2013. The PTF sample has great potential for addressing several distinct questions. The overriding goal is to study ensemble properties of different comet groups. In this work, we compare activity occurance in both comet groups of 115 SPCs, and 66 LPCs. In particular, we compare our findings with the latest published surveys on comets, such as Bauer et al. (2017) and Kelley et al. (2013).

2. STUDY OF THE ACTIVITY OF SPCS AND LPCS

The sample of ~ 120 short period comets mostly comprising Jupiter Family Comets (JFCs) was detected through an approach explained in (Waszczak et al. 2013). It exceeds the number of comets in previously published work targeted surveys as stated above, making our sample statistically important to test different hypotheses, as we propose in the following. The number of comets represents more than 20% of the total known short period comets (https://physics.ucf.edu/ yfernandez/-cometlist.html) . In addition, as shown in Figure 1, the cumulative perihelion distribution of this group of comets is comparable to the cumulative perihelion distribution of the total known comets, showing the homogeneity of our sample in the perihelion space, for the most part. In the following we present the first, preliminary results on the activity in relation to dynamical properties of SPCs and LPCs. In particular, we would like to point out the potential of this data sample, and such robotic surveys into studying transient objects in the solar system.

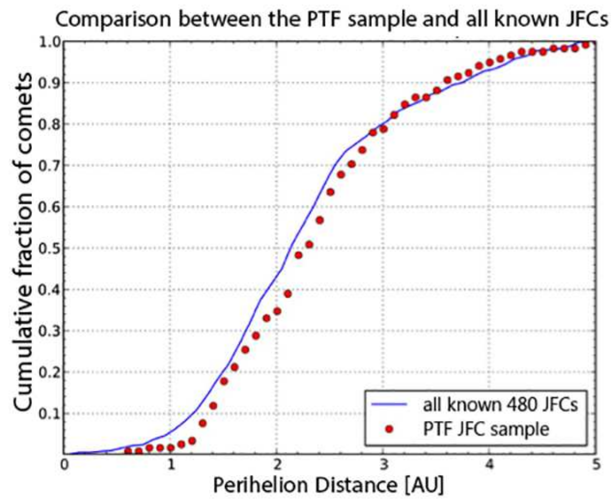

Fig. 1. Comparison of the cumulative perihelion distribution of our current 120 PTF JFCs (closed red circles) and all 480 known JFCs (solid blue curve). The curves match well indicating that our sample perihelion bias is representative of the overall one.

2.1. *Activity detection technique*

In this study, we consider a comet active if it shows any form of extendedness, whether symmetric or not. However, we do not attempt at detecting comet dust morphologies, or localizing them. At a high enough angular resolution, a coma is detected with a surface brightness distribution that decreases with distance from a central source. In the rest frame of the nucleus, dust grains move away from the surface, possibly forming tails or trails, on larger time scales. The existence of trails or tails could indicate activity that was ignited in the previous months or year, however the presence of a coma implies ongoing current activity. In our classification technique, we labeled 'active' a comet image showing any sign of extendedness, whether current (coma) or past (trails/tails).

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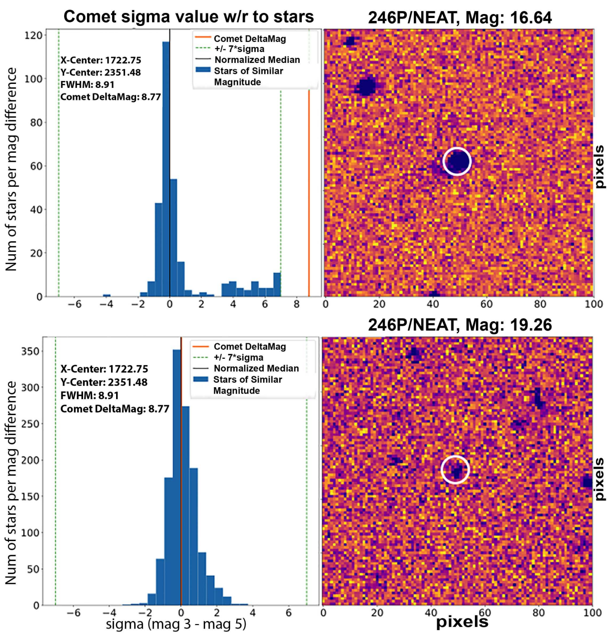

Fig. 2. Two examples of the same comet 246P/NEAT once detected in its active phase (top), and once detected in its dormant phase as not active as compared to field stars (bottom). Right panels show a subframe centered on the comet. Left show a histogram of the field stars of the mag-diff metric; the orange vertical line shows the mag-diff value of the comet, and the green vertical line is the 7-σ cut-off position.

Our combined SPC and LPC sample comprises 2000 images, in the R- and g-band. We present and compare two approaches to diagnose extendedness: Magnitude difference (mag-diff) and full width at half maximum (FWHM) sigma difference. While the mag-diff metric is a new introduction to activity detection, comparison of comet brightness profile or FWHM to background stars has been applied in multiple previous works already (e.g. Meech et al., 2004; Snodgrass et al., 2008; Mazzotta Epifani et al., 2009). Both metrics use a σ-outlier rejection technique that we detail next; in addition, we used visual inspection on each image to verify their validity. For the mag-diff metric, we computed the difference between two magnitudes in two apertures, a 3 pixels radius aperture (mag3), and a 5 pixels radius aperture (mag5). This is equivalent to the flux ratio in these apertures. We then compared it with the mag-diff of field stars with magnitudes similar to the comet. In particular, we looked at the mag-diff distribution of all stars in the field, and computed its median value, and standard deviation. We looked at the deviation of the comet mag-diff value from the star mag-diff distribution. We subtracted the comet mag-diff value from the median of the star mag-diff and divided it by the standard deviation of the mag-diff distribution of the field stars. The resulting ratio is an estimate of the separation (in units of σ) of the comet's extendedness with respect to point sources in the field.

Figure 2 shows two cases of comet 246P/NEAT, when the comet is active (top) and when the same comet is inactive (bottom). For each subframe centered on the comet (right panels), we plot the histogram of the stars, which magnitudes are within 1 mag. of the comet (left panels). In this metric, a comet showing a mag-diff $\sigma > 7$, is considered to show extendedness, and is labeled as active in that frame. We explain the rational behind our threshold of 7 σ in section 2.2. A similar approach was used for the FWHM sigma difference metric. In that case, we looked at the ratio of FWHM of the comet over the median of the star distribution. Similarly to the mag-diff approach, the sigma separation of 7 between the comet FWHM and that of the stellar distribution was used as a metric to label the image as active or inactive. We do not show a specific figure for the FWHM, however, the result is similar to what is shown for mag-diff σ plots in 3. In all cases, we used the iPTF pipeline, where the magnitude values, FWHM, and centroid positions were determined using SExtractor (Bertin & Arnouts, 1996. At the end, we considered any comet that showed extendedness in any of its R-band or g-band images to be active; on average, there are more than 10 images per comet in our sample.

In the future, to better test the robustness of our technique, we will search for available mid-IR images of active PTF comets in order to compare the threshold of detecting activity in both wavelengths regimes. Since mid-IR images are more suited at detecting dust emission, we expect visible images to have a higher threshold than for the IR. With that in mind, our survey might be missing activity that is otherwise detected in the mid-IR. Also, future and deeper observations and programs such as the Zwicky Transient Survey, ZTF (e.g., Bellm et al., 2019), the Legacy Survey of Space and Time, LSST (e.g., Ivezić et al., 2019), Roman Space Telescope, WFIRST (Holler et al., 2018), or James Webb Space Telescope (Meech et al., 2017, Holwerda et al., 2019) are expected to detect activity at even higher magnitudes.

In the future, in order to further confirm the robustness of our metric, we plan on testing our method against PSF matching as used in Kelley et al. (2013), as well as the extendedness criterion as estab-

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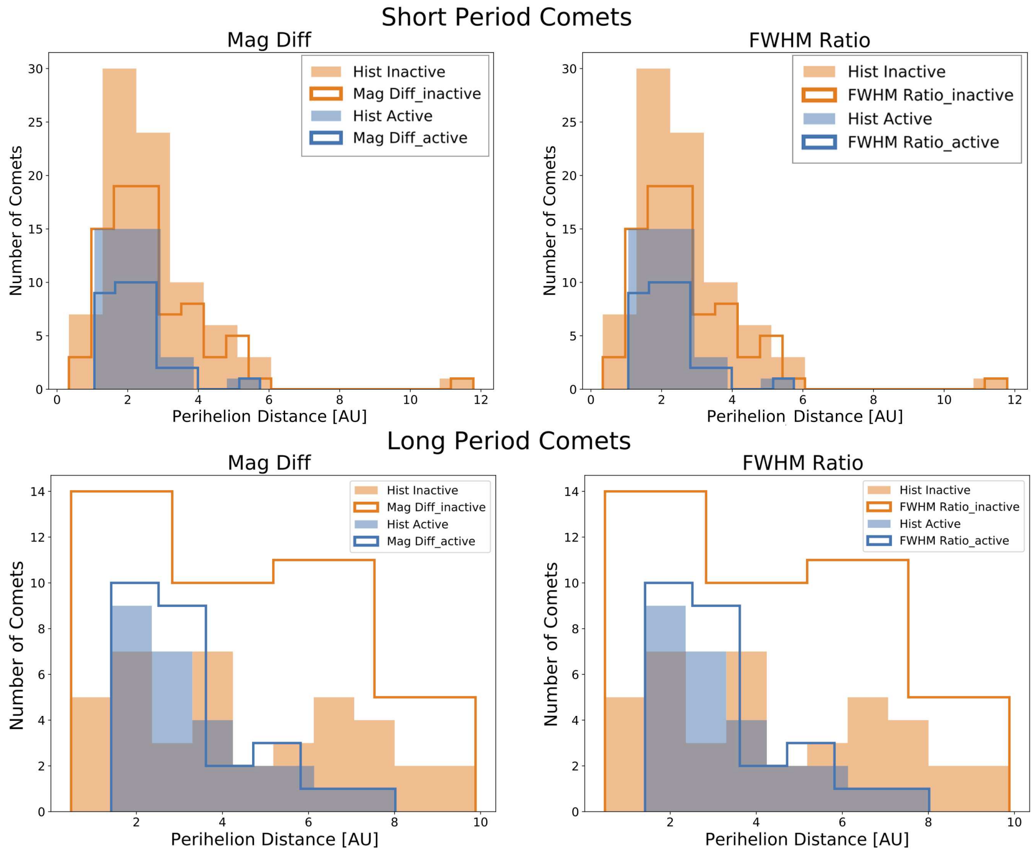

Fig. 3. (top panel) Histograms for the SPCs showing the active comets in blue vs. the non-active comets in yellow using the mag-diff metric (left) and the fwhm σ metric (right).The blue and orange box lines represent the Knuth histograms, where a Bayesian approach is used to determining the optimal bin width of the histogram. (bottom panel) same as above but for LPCs.

lished in Waszczak et al. (2013). Very importantly, we will also apply our method on different images as to avoid the problem of crowding and source contamination. In the following, we discuss the results obtained with both our approaches; we compare our findings on activity of SPCs with those in Kelley et al. (2013); and we contrast activity in both groups of SPCs and LPCs of our sample.

2.2. *Results*

We found that the two metrics, the mag-diff and the FWHM σ difference, resulted in very similar identifications. The FWHM metric tends had a false positive detection rate of active comets not exceeding 4%, with these identifications likely being false positives. Statistically, both metrics showed identical distributions, as can be seen in the left and right panels of the histogram of Figure 3. Only 6 out of 120 SPCs were labeled active solely in the FWHM metric, while just 1 out of 70 LPCs was labeled active solely in the FWHM. All comets labeled as active in the mag-diff metric were also found to be active in the FWHM metric. For our final results, we consider active comets that were identified as active in both metrics combined, or equivalently for this sample, those that were identified as active in the mag-diff metric.

As stated above, we used visual inspection to confirm our findings. We found that for the large majority of the images, extendedness can be visually ruled out or confirmed for at least 85% of the images. This is the case because either the comet is faint (mostly for mag > 19), and looks like a small point source, or the comet is bright, large, extended with clear trail, tail or coma features (mostly for mag < 17). In the case where the visual inspection was not deterministic, the sigma value of either of the metric ranged mostly between 5 and 8; for that reason we decided to choose a sigma of 7 as a delimiting factor for activity. With that respect, we might be underestimating the number of active comets by roughly 5%. However, we also expect to have false positives as well by 5% to 10%, especially in the case of low quality

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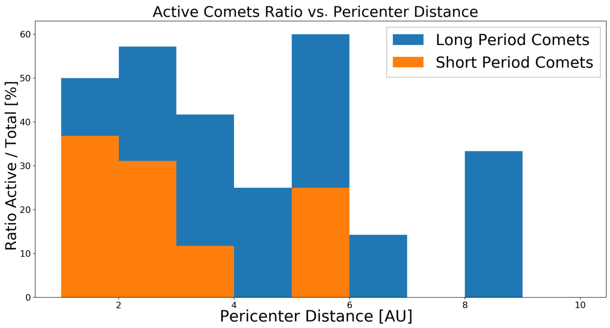

Fig. 4. Ratio histogram comparing the percentage of active comets for SPCs and LPCs per perihelion bin. Orange represents the ratio of active SPCs over the total number of SPCs, while the blue color represents that of the LPCs.

images, or source crowding. More tests and comparisons are planned to verify and strengthen the metric used, or a combination of a few.

We report that $27\% \pm 4\%$ of the SPCs showed activity at least once in the observed period of time. As shown in Figure 3, for the SPCs, the highest activity is found for comets around 2 A.U. Most comet activity was found for comets with perihelia between 1 A.U. and 3 A.U, where 24 out of 82 observed comets were confirmed as active (30%), with 3 more unconfirmed detections. In contrast, only 4 out of 27 observed comets (15%) with perihelia greater than 3 A.U. where found be active in our sample. All three comets with perihelia smaller than 1 A.U. did not show activity in the images. Since the detection probability for activity decreases with fainter comets, the above found fractions should be thought of as lower limits rather than deterministic values.

The targeted Spitzer survey of Kelley et al. (2013) sampled comets between 3 A.U $< r_H <$ 7 A.U. They found that, in their sample of 89 JFCs comets with q $<$ 2.5 AU, 12% were active, and none of the 30 comets with q $<$ 1.8 AU were active (their figure 11). In comparison, in our sample, we only have 10 comets available in the same r_H range and q $<$ 2.5 AU; out of those only one comet was found to be active. So although this comes to 10%, similar to what is found in Kelley et al. (2013) these low number statistics leave us unable to conform their results. However, we found that out of the 34 observed JFCs with q $<$ 1.8 AU, up to 11 comets are active for $r_h < 3$ A.U, with 8 visually confirmed detections. This means at least 24% of these comets showed signs of activity at least once in our images. This can be considered a high activity rate in comparison to the highest activity rate of 31% for SPCs around 2 AU. In short, we are unable to statistically confirm the results of Kelley al. (2013) due to our low number statistics in their targeted heliocentric range. However the fact that our active comets are at $r_h < 3$ AU supports their findings - a result in agreement with Mazzotta Epifani et al. (2009) whose study is based on a literature search. To explain their finding, Kelley al. (2013) proposed that relatively more volatile ices are lost for comets that approach the Sun more closely during their perihelion passages. They also suggested that comets with small perihelion distances have a thicker insulating surface than comets with larger perihelion distances.

In contrast, we found that more LPCs are active on average than the JFCs, with an activity rate of $38\% \pm 5\%$. Comets with perihelion distances of about 3 AU exhibit the largest ratio of activity, up to 50% of all observed LPCs. Though their activity is reduced at greater perihelion distances, they stay active well beyond the JFCs. This is in particular shown in the ratio histogram in Figure 4. However, at large perihelia, we are working in the regime of small number statistics and would not draw conclusions from our findings. As expected, at large distances, our sample is not complete, and the apparent magnitudes of these comets become the limiting factor into detecting any activity. De-biasing the sample will be needed in order to extrapolate our results to the population of comets at large.

We found that the PTF LPCs sample has different properties from historical samples (like Everhart sample (1967), and Hughes sample (2001), and shows similarities with the Francis (2005 - 31 LPCs) sample and the Bauer et al. (2017 - 56 LPCs) sample, which is the latest statistical study published on comets including LPCs to-date. Figure 5 shows that our PTF sample contains a large number of comets at large perihelia and a smaller number of bright comets (H $<$ 8). Importantly, our sample implies there is a distinction between old comets and new comets, which is not the case for Francis (2005). We compared activity in two old LPCs and new LPCs separately. We found that the percentage of activity was higher in new comets with 50% of all 28 new comets found active, while only 29% of the 38 old comets were found to be active.

For LPCs, we also address a long standing question on whether comets have enhanced activity at positive true anomalies or post-perihelion. Kelley et al. (2013) and a number other previous studies (e.g. Mazzotta Epifani et al., 2009); suggested this is the case for JFCs. We will look into that for JFCs in future work, and we hope to be able to judge whether this trend remains invariant with perihelion and he-

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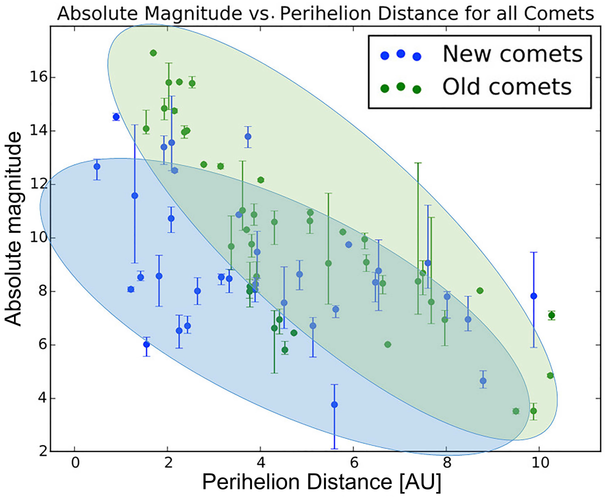

Fig. 5. Absolute magnitude estimates of both old LP comets (green dots) and new LP comets (blue comets) in function of perihelion distance in AU. Filled circles indicate an average value per comet over all images found for the comet; errorbars show the range of magnitudes derived from different images of the same comet.

liocentric distance. When tested on our LPC sample, we found that only 7 out of 25 active comets exhibited activity before pre-perihelion passage, while the majority showed activity post-perihelion passage, in agreement with the above mentioned papers. An example of how absolute magnitude changed pre- and post-perihelion is shown in Figure 6. In this figure, the absolute magnitudes were computed following Francis (2005)); the comet was labeled new if the semi-major axis a was greater than 10,000 A.U., and old for $a < 10,000$ A.U. The errobars show the variation in the H magnitudes as found over different epochs, whenever multiple observations of the same comet were available. In the future, we will distinguish between dynamically new, young, and evolved Levison et al. 1996.

3. OTHER POTENTIAL RESULTS FROM THE PTF SURVEY

The PTF sample comprises small and large perihelia comets detected at different epochs, thus different heliocentric distances, phase angles and true anomaly angles. For that reason, it is ideal to tackle questions as the ones addressed in this proceedings. Here we list a few more questions that could be addressed using current and future surveys, such as ZTF (`https://www.ztf.caltech.edu/`) and LSST (`https://www.lsst.org/`), and others.

[1] Do different dynamical comet families show different absolute magnitude distributions as could be suggested in Figure 5? At small perihelia < 3.7 AU, the old comets seem to exhibit greater magnitudes (lower brightness) than new comets (higher brightness). This trend disappears at perihelia larger than 3.7 AU, where both comet populations exhibit similar distributions in absolute magnitude vs. perihelia space.

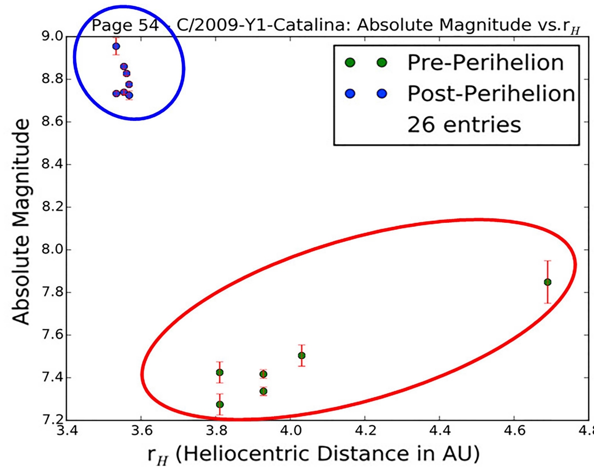

Fig. 6. Example figure of absolute magnitude H as a function of heliocentric distance for the LP comet C/2009 Y1 (Catalina). Pre-perihelion data points are green and post-perihelion measurements in blue. It is clear that in this case the comet was brighter before its perihelion passage.

[2] Does dust activity increase with size as suggested by Bauer et al. (2017)? It is possible to look for correlations between the nuclear size and the above-discussed hypothesis on activity as a function of orbital parameters, derive sizes when possible and use the literature for well-identified sizes (eg., Snodgrass et al., 2011; Weiler et al., 2011; Fernández et al., 2013; Bauer et al., 2017;...)

[3] Are LPCs active at a larger distance than SPCs? Do they become more active after perihelion passage A'Hearn et al. (2012)? Are LPCs intrinsically brighter than SPCs as suggested by Brasser and Morbidelli (2013)?

4. DISCUSSION

We proposed and tested a new metric for detecting cometary activity, and applied it to the large and uniform PTF sample with the purpose to test the inhibitors and drivers of activity in a statistical manner. Our first results on the distribution of the different comet groups in perihelia space, and differences in the activity of the these groups show distinctive characteristics that are helpful in assessing and comparing the properties of different groups.

Our preliminary results show that more LPCs are active than SPCs, and this stays true over all perihelia. LPCs seem to also show activity at larger perihelia than JFCs. This is implying that LPCs become more readily active than the JFC population. Similarly, there is an indication that new LPCs might indicate a higher level of activity then their older counterparts. Our sample seems to agree with the finding of Bauer et al. (2017) that there exists a larger number of LPCs at q < 1.5 AU than previously thought.

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