Comet C/2014 Q2 (Lovejoy) photometric observations

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1. INTRODUCTION

C/2014 Q2 (Lovejoy) is a long-period comet discovered on August 17th 2014 by Australian amateur-astronomer Terry Lovejoy. Discovery pictures were taken by 8-inch Schmidt-Cassegrain telescope placed in his private roll-off roof observatory in Brisbane, Australia. At the moment of the first detection, Comet Lovejoy was as bright as 15 mag and located in the constellation of Puppis.

It orbits Sun in very eccentric ecliptic orbit, which takes more than 13 500 years and not approach closer than 1.29 AU to our star. In the line with expectations, C/2014 Q2 has become one of the most attractive comets in the northern hemisphere over the past years. Its favorable position in the sky enabled Polish observers to more than half a year time when the object was visible even in small optical instruments. It probably resulted in a huge popularity of this comet.

Exact orbit elements of C/2014 Q2 (Lovejoy) for epoch 27th June 2015 are presented in the table below. Calculations are based on 6600 observations achieved by Minor Planet Center.

C/2014 Q2 (Lovejoy)	
Perihelion date:	2015-01-30.06757
Perihelion distance:	1.2903763 AU
Eccentricity:	0.9977291
Inclination:	80.30132°
Argument of perihelion:	12.39551°
Ascending node”	94.97570°

First observations occurred soon after the discovery – in the end of August 2014 comet brightness was estimated at about 14 mag and a month later even 12 mag. When in the middle of November 2014 in 2 weeks time its brightness increased from 10 mag to more than 8 mag, it seemed obvious that Comet Lovejoy would be even brighter during its past-perihelion passage through northern hemisphere than we first expected. This time also a short tail (about 0.3° in length) was detected, but visual observations of this structure were made freshly after full moon on December 6th. During this month it was growing to establish constant value of 1 degree by the end of the year. Before 2015, the comet brightened to about 5 mag, but was not visible in Poland until the last week of the year – in the middle of December it was rising only a few degrees above the horizon.

On January 7th it approached the shortest distance to the Earth, which was calculated as 0.47 AU. Although, because of the full moon only two days before, comet tail was not discernible in the first week of the year. Afterwards, it was estimated to be about 2°-3° in length. Finally, in mid-January, the maximum brightness of the comet was established at 3.9 mag. Despite the decrease in brightness in the following weeks, at the beginning of March it was still brighter than 6 mag and the last report, estimating the object’s visibility to the naked eye, appeared on 10 March. Therefore, it can be said that for 4 months Polish observers could see Comet Lovejoy form in the dark sky even without any optical equipment. The comet tail was observed for 2 following months and was not visually seen after the middle of May. Last binocular observations were reported even in the end of July, when the comet had a brightness of approx. 10 mag, but later the object remained observable only by telescopes.

2. OBSERVATIONS

2.1. Coordinated Polish observations

After the fusion of Sekcja Obserwatorów Komet PTMA (SOK PTMA) and Centrum Obserwacji Komet (COK), the new collective comet observation archive was established. In the period from December 2014 to October 2015 we received 232 brightness measurements of comet C/2014 Q2 (including 1 estimation of comet nuclei brightness), 230 measurements of its coma diameter and 228 estimations of comet's condensation degree. 230 observations were made visually, two remaining – using CCD/DSLR photometry. Comet C/2014 Q2 (Lovejoy) observing campaign, organized by SOK PTMA and COK, was attended by 23 observers from Poland. Observers activity is summarized in the table below.

Observer name	Location	Instruments used	Number of observations
Leszek Benedyktowicz	Kraków	3B 6B 15L	13
Jerzy Bohusz	Myślin	20L 38L	15
Jarosław Dygos	Czernice Borowe	6B	2
Tomasz Fajfer	Toruń	7B	17
Marcin Filipek	Jerzmanowice	5B 10B 25L 40L	28
Marcin Górski	Kurznie	5B 15R	3
Piotr Guzik	Kraków	E 5B 33L	49
Paweł Kankiewicz	Kielce	35T	1
Wacław Moskal	Jasło	6B	2
Paweł Nowak	Bystra	5B	1
Piotr Ossowski	Ostrów Wielkopolski	7B	2
Mieczysław Paradowski	Lublin	4B 5B 15L	10
Jacek Powichrowski	Knyszyn	E 5B 6B 35L	15
Maciej Reszelski	Szamotuły-Gałowo	7B	1
Kacper Rosół	Strzelce Krajeńskie	5B	1
Zbigniew Rzepka	Lublin	4B	2
Mikołaj Sabat	Kielce	7B 11B 15L 35T	6
Marcin Siekierko	Michałowo	17L	2
Mieczysław Sikora	Lublin	6B	2
Robert Szczechura	Gorzew	5B	1
Tomasz Ściężor	Kraków	5B 6B 10B	52
Mariusz Świętnicki	Zręcin	7B 25L	5
Artur Wargin	Bydgoszcz	6B 10R	3
Meaning of symbols: E – naked eye, B – binocular; telescopes: L – Newton reflector, R – refractor, T – SCT Numbers present aperture of an instrument in centimeters. In blue were marked instruments used to CCD/DSLR photometry.			

As it turns out, a while after the fusion of Sekcja Obserwatorów Komet PTMA and Centrum Obserwacji Komet, a significant record in the amount of collected observations was broken. 232 reports received from observations of C/2014 Q2 (Lovejoy) is the best result since the outburst of comet 17P/Holmes, which in the framework of SOK (since 2008 COK) in 2007 and 2008 was seen 393 times. This puts Comet Lovejoy in 10th place among the most frequently observed comets in the history of Sekcja Obserwatorów Komet PTMA. Last time, similar popularity was gained by the long-term comet C/2004 Q2 (Machholz), which reached maximum brightness equal to 3.4 mag in January 2005. In total, during those observation campaign observers sent to SOK PTMA 440 reports of Comet Machholz observations between 2004-2005. Interestingly, apart from the similarity in the name, which provides a similar time of discovery of both objects through the year, Comet Machholz had another features comparable to recently observed C/2014 Q2 (Lovejoy). Both objects were moving on a similar track in the sky and had been fading incredibly slowly. Also their orbits in the inner solar system have much in common: on January 24th 2004 Comet C/2004 Q2 (Machholz) was in the perihelion approx. 1.21 AU from the Sun, while C/2014 Q2 (Lovejoy) - January 30th 2015, approx. 1.29 AU in perihelion. Comet Machholz closest approach to the Earth took place on January 5th 2005 in a distance of approx. 0.35 AU, while Comet Lovejoy - January 7th 2015 in approx. 0.47 AU.

Despite the undeniable similarities of both objects and the fact that in their day they were among the most popular destinations for observers from Poland, 10 years ago above 200 observations more for Comet Machholz were reported. Probably the difference would be much less if C/2014 Q2 (Lovejoy) went above the horizon earlier. Better C/2004 Q2's position ten years ago resulted in its visibility sufficient for observers' estimation during the entire autumn of 2004, which was not possible in 2014 for Comet Lovejoy…

The time has come for transfusion individual "records" that were established by observers in SOK PTMA while tracking the comet C / 2014 Q2 (Lovejoy) on the Polish sky:

- First observation (25th Dec 2014) – Piotr Guzik, Mariusz Świętnicki;
- Last observation (2nd Oct 2015) – Marcin Filipek;
- The longest period of observation (6th Jan 2015 – 2nd Oct 2015) – Marcin Filipek;
- The highest number of observing nights (52) – Tomasz Ściężor.

2.2. Methods of visual comet observations

All the observations submitted to Sekcja Obserwatorów Komet PTMA were done using one of the standard methods, acceptable by International Comet Quarterly (ICQ). Furthermore, properly obtaining a total visual magnitude estimate of a comet, is a difficult process and due to the extended size of the comet's coma and to the combination of diffuse coma plus central condensation, some measurement errors are inevitable. But as shown in section 3.1., the differences in magnitude estimations do not exceed average norm of 1 mag. All of the ICQ's acceptable methods compare a comet's brightness with that of comparison stars from catalogues of visual magnitudes, or from other resources that contain such data.

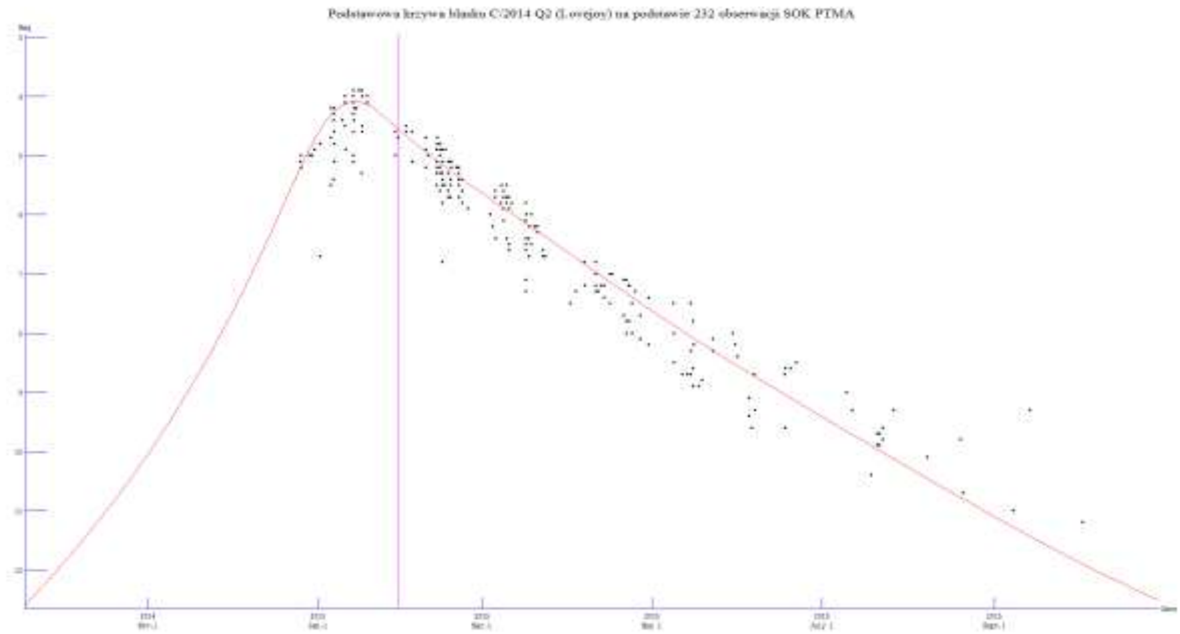
For visual observations of comet C/2014 Q2 (Lovejoy), observers in SOK PTMA have used three different methods of magnitude estimations, presented below.

- **Van Biesbroeck-Bobrovnikoff-Meisel / Bobrovnikoff Method – *130 observations***
  VBM extrafocal method is correct when the comet shows little coma. With this method, which is sort of an "equal-out" procedure, which means that observer slightly de-focuses both the comet and comparison star(s) the same amount until comet and star appear about the same size.
- **Morris Method – *63 observations***
  This method was developed by Steve O'Meara and Charles Morris in the late 1970s that essentially combines the above "In-Out" and simple "Out-Out" methods into a single, better extrafocal procedure – in which the comet is defocused in the amount to smear out the nuclear condensation and overall brightness gradient, making the defocused comet image as uniform as possible in surface brightness.
- **Vsekhsvyatskij-Steavenson-Sidgwick / Sidwick Method – *37 observations***
  The VSS method involves a comparison the memorized in-focus image of the comet to a de-focused imaged of a comparison star, which is de-focused to the same coma size as the in-focus comet.

3. RESULTS

3.1. Comet brightness

First of all, object brightness is the most elementary and one of the most important feature in analysis of every comet. Presented light curve of comet C/2014 Q2 (Lovejoy) is based on the data taken from 232 magnitude estimations done by observers from Sekcja Obserwatorów Komet PTMA between December 25th 2014 and October 2nd 2015.



All 232 observations are presented in a function of time. As can be seen, the differences in magnitude estimations of the comet done by different observers do not exceed 1 mag, outside the single exceptions, which shows good accuracy of measurements. The maximum brightness of 3.9 mag comet was obtained by C/2014 Q2 between 13th and 16th January. It is less about a week after the closest approach to the Earth and two weeks before comets perihelion.

To make our interpretation properly, we cleared the light curve from misleading impact of varying distance between the comet and the Earth. Observed brightness was reduced to the so-called heliocentric brightness, which gives an idea of how the final result would appear if the observer was located at a constant distance of 1 AU from the comet. The chart below shows the change in the heliocentric brightness of comet C/2014 Q2 (Lovejoy) per unit of time:

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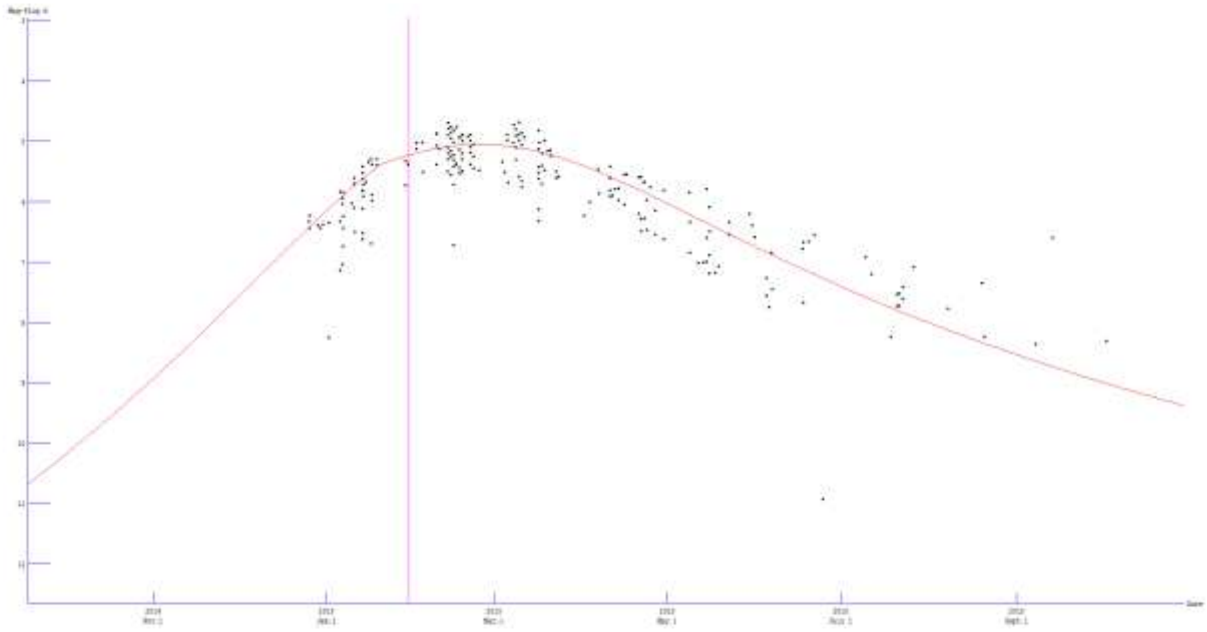
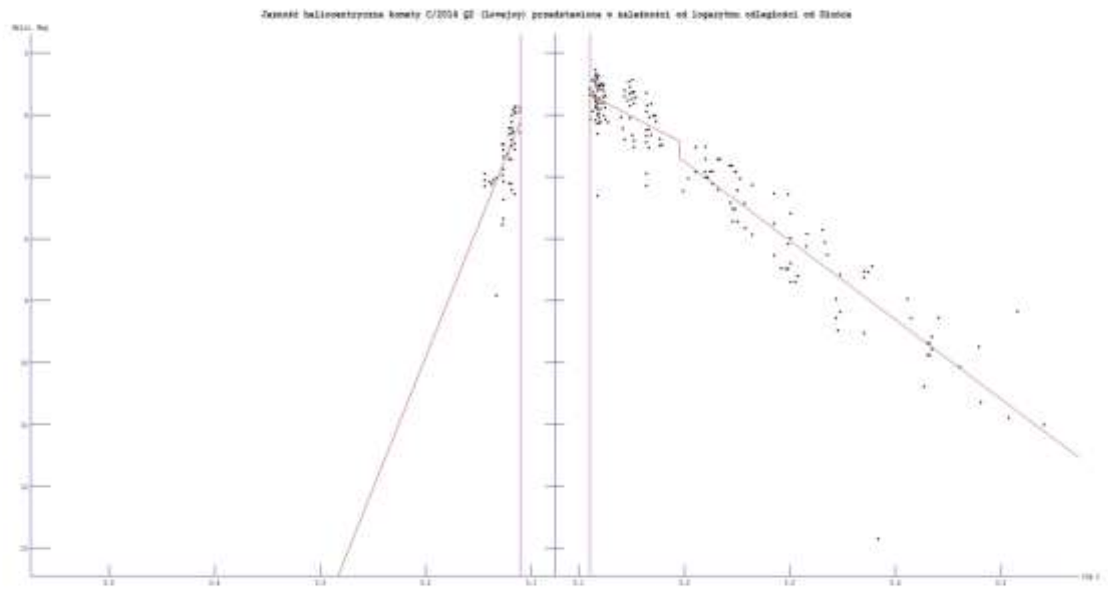


As can be seen from the curve, Comet Lovejoy reached its highest heliocentric brightness of approximately 5 mag about 20 days after perihelion. In order to see how the activity of the comet was changing during the observed period, data shown above will be presented in depending on the logarithm of the distance between the comet and the Sun, as in the formula below:

$m = H_0 + 5 \log d + 2{,}5\, n \log r$

where:
m – observable magnitude
H_0 – absolute magnitude
n – comet activity parameter
d – distance to the Earth
r – distance to the Sun

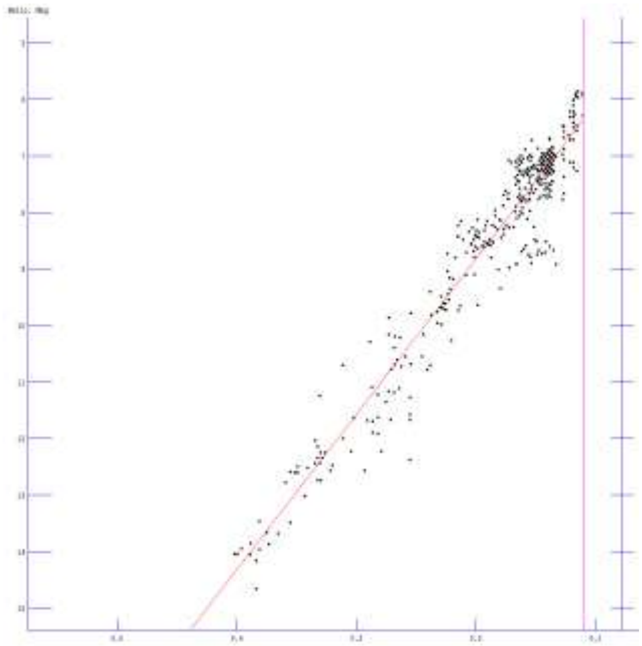
Then we get three line segments:



Generated segments might be described by two formulas, presented below:

- **[-36d ; 0d]:** 1.38 mag + 5 log d + 37.58 log r
- **[0d ; +60d]:** 4.67 mag + 5 log d + 3.97 log r
- **[+60d ; inf.]:** 4.19 mag + 5 log d + 7.8 log r

Obtained values suggest a significant decline in comet's absolute magnitude after its perihelion. Differences amounting to 3 mag should be regarded as incredibly high. The solution to this problem may lie, in the manner of observations archiving by SOK PTMA - we have only the observations made during object's visibility from Poland. The first observation in SOK PTMA was made 36 days before perihelion. Such a short range taken into consideration when creating the first line segment can falsify the results. Therefore, the accuracy of calculations would be increased by adding observations collected by Comet Observation Database in the period August 27th 2014 - December 31st 2014. Thus arose the following graph:



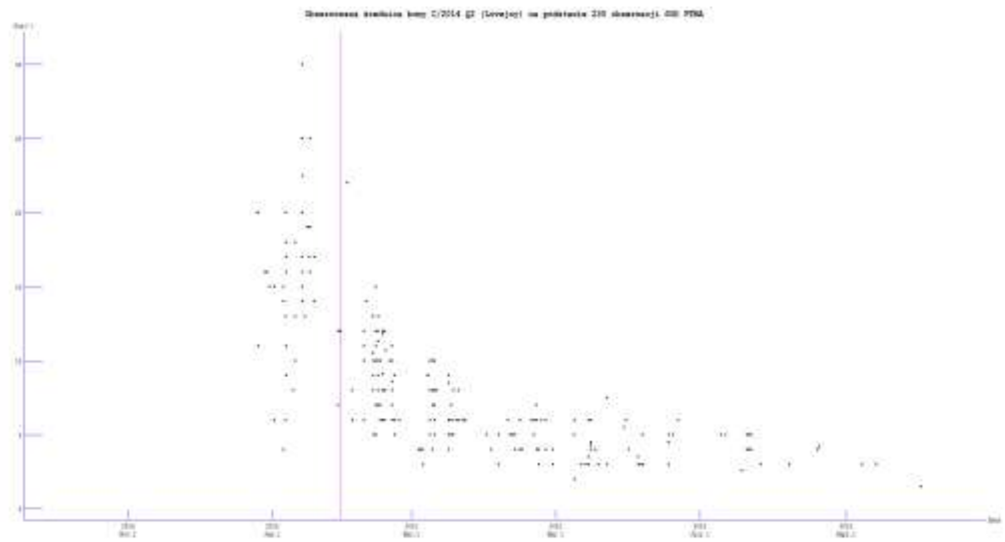
Presented line segment is equal to the formula:

[-126d ; 0d]: 3.32 mag + 5 log d + 22.5 log r

As can be seen above, comet C/2014 Q2 (Lovejoy) showed an extremely high activity before perihelion. This behavior may suggest existence of large ice deposits, which, during sublimation, ensure high emission of gas from its nucleus. In the period of approx. 2 months after perihelion, the comet both activity and its absolute magnitude noticeably declined. The decrease of approx. 1.35 mag in absolute magnitude is equivalent to a decline in albedo of the comet's nucleus. It may be inferred that some sources of volatile gas have reached the end or "blocked" during its closest approach to the Sun. Later, about 60 days after perihelion, absolute magnitude rose again of less than half a magnitude, as well as activity of the comet doubled. What could be the reason? Perhaps a new bed of ice had activated or this very active one resumed emission. It seems that such a large oscillations of activity and albedo could be caused by emissions depending on several major sources located close to the comet's surface, which, as it was approaching the Sun, were sublimating rapidly and at the turn of January and February 2015 these regions have deactivated. Activity of C/2014 Q2 in the first 2 months after perihelion was extremely low, which can support this interpretation. The subsequent increase in activity could be caused by an activation of ice deposits located in a deeper layers of the comet's nucleus.

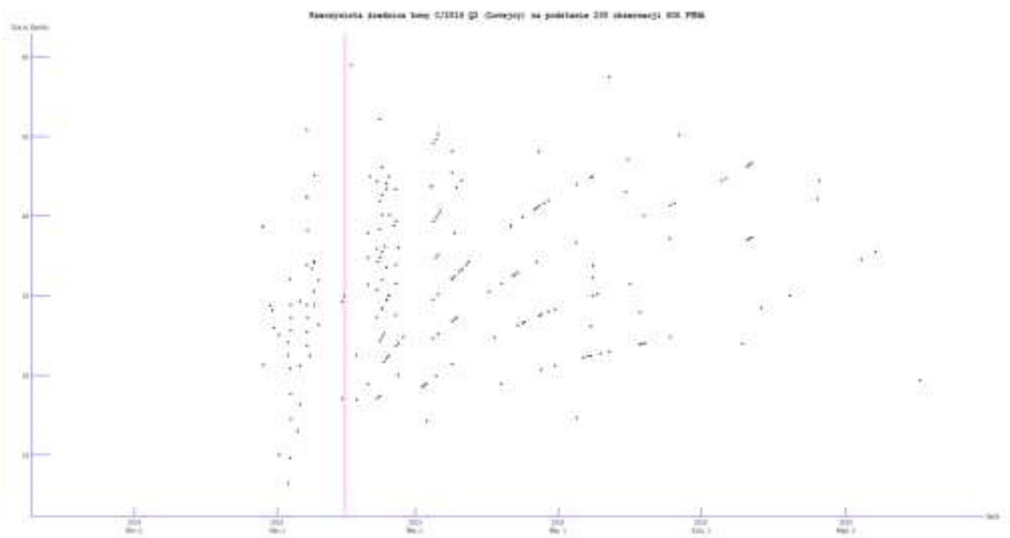
3.2. Coma observations

Comet's behavior is usually in a constant change. One of the most productive feature for an observer is coma. This formation, surrounding the nucleus, is quickly responding to almost every changes that took place in the nucleus surface. Directly from observations we are able to predict the most general composition of the object, estimating its approximate gas to dust emission ratio. It all have a response in comet's coma appearance and dimensions.



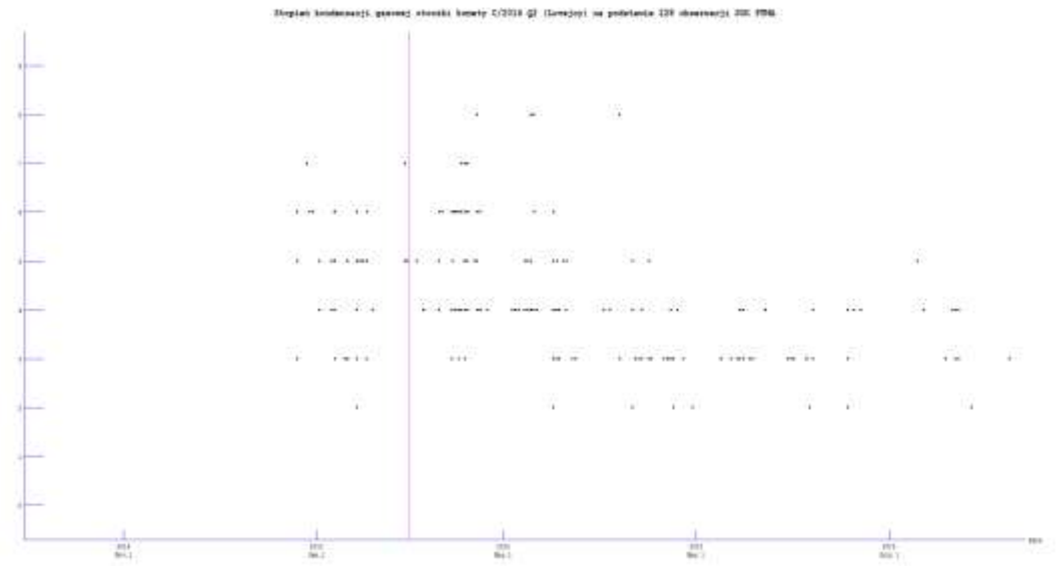
The chart above shows data from 230 estimations of cometary coma diameter presented in arc minutes. As you can see, the largest coma dimensions were observed shortly before perihelion, which is understandable in result of comet's closest approach to the Earth in early January. From that time, the object was moving away from us, which justifies a significant decrease in the coma diameter spotted in the sky after the perihelion passage.

To clear a confusing factor caused by variable distance between the object and the Earth, it is necessary to reduce the data, as in the chart below:



Evolution of the coma diameter, determined apart from the distance changes (such as the comet was in a constant distance from the Earth) are presented as multiples of the Earth's diameter. It can be inferred, that shortly before perihelion the real diameter of the coma was approx. 360 000 km (about 30 diameters of the Earth) and it was constantly rising until reaching the maximum size of approximately 540 000 km (approx. 45 diameters of the Earth) in mid-February 2015 (or 2 weeks after perihelion). Over the next months, the coma diameter stabilized at the value no greater than approx. 480 000 km (40 diameters of the Earth) and from May it was decreasing slowly under 360 000 km. In the summer it stabilized at the level of approx. 300 000 km, which was remained to the end of the observation period.

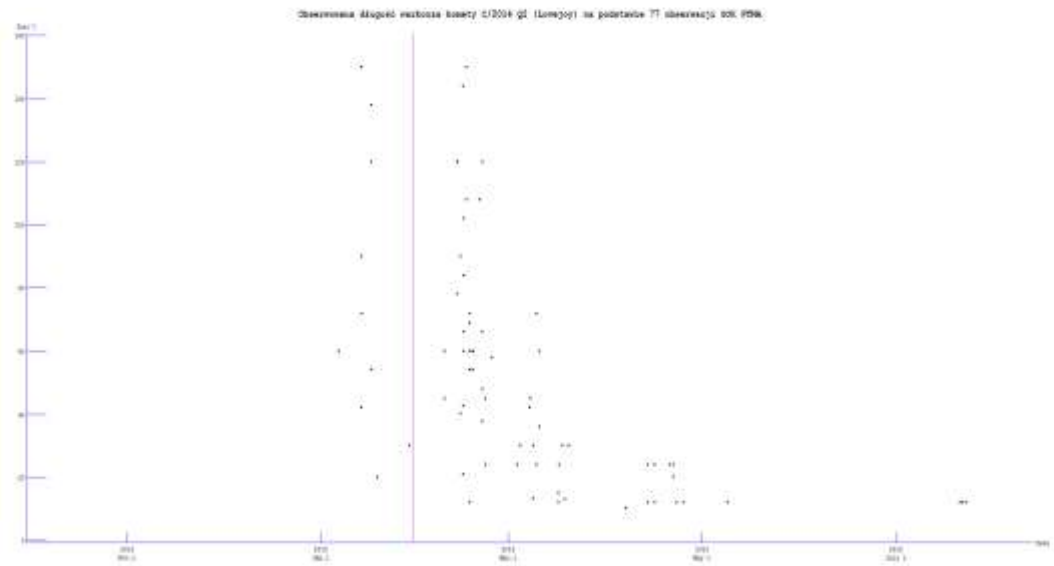
In order to get a general view on changes that were taking place in the nucleus of the comet, we should analyze the graph shown below, which shows the degrees of coma condensation:



At the turn of years 2014 and 2015 the degree coma condensation was estimated at DC=5, which means a noticeable brightening in the center of the comet's atmosphere. In February 2015 it became even more apparent and the condensation of C/2014 Q2 was assessed to reach approx. DC=6. In the beginning of March, this value was reduced to DC=4 and in mid-April even to DC=3, which suggests the presence of a slightly fuzzy coma, without distinguishing any conspicuous brighter spot in the center. The prior increase of brightness in the coma center could indicate a stronger gas emission from the comet's nucleus shortly after perihelion, which confirms previous inferences of noticeable increasing comet's activity at the time.

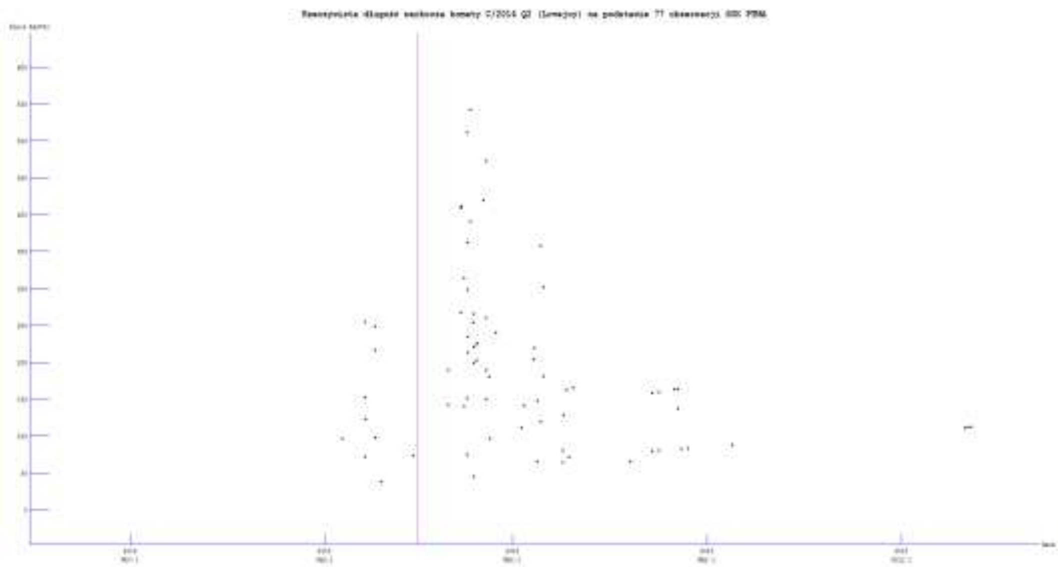
3.3. Observations of comet tail

Observations of Comet Lovejoy's tail would bring us some information about gas and dust emission from the nucleus. Tail's position angle provide us to predict whether ion or dust tail is visible and the tail length estimations are closely related with comet activity.



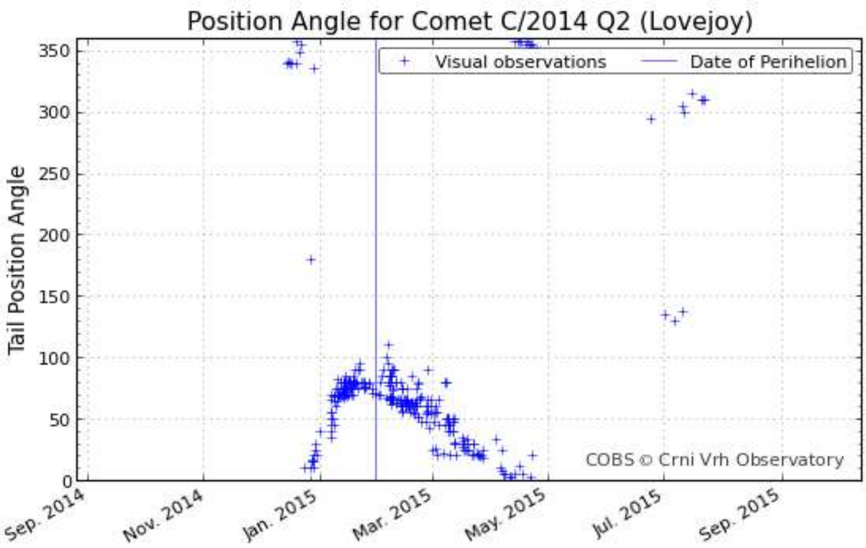
The graph above shows specified in arc minutes observed length of the C/2014 Q2 (Lovejoy)'s tail, based on 77 estimations reported to SOK PTMA. It obtained the highest size over several days before and after perihelion of the comet and stayed observable until May. Single observations confirming the visibility of this formation appeared also in July.

To make our interpretation properly, we cleared the graph from misleading impact of varying distance between the comet and the Earth:



The actual length of the tail, which was developed by C/2014 Q2 (Lovejoy), is presented as multiples of the Earth's diameters. It is clearly seen that in the first weeks of the object visibility in Poland, tail had a length of approx. 200 Earth diameters, which means ~2 400 000 km. About two weeks after perihelion a sharp increase in the length of the tail was detected. Approximately it was approx. 5 100 000 km (425x Earth's diameters) in length, although some observations indicated a maximum value equal even more than 6 000 000 km (500 Earth diameters). After another 2 weeks, the length of the tail decreased to approx. 3 000 000 km and remained at that level until mid-March. Then its length almost halved to the value of approx. 1 800 000 km. It maintained at this level until May and, probably, after a slight decline of ~400 000 km, it stayed until July, when was seen for the last time. A significant increase in the length of the comet tail after passing through perihelion was expected and seems to confirm earlier observations, confirming huge activity of Comet Lovejoy in February 2015. However, according to visual observations, its maximum length, oscillating at around 6 million km, is the an average result in the case of long-period comets.

To define, which type of the comet tail: gas or dust, was seen during C/2014 Q2 observation campaign, we plotted on the graph below data of comet tail's position angle estimations:



In order to increase the accuracy of our results, we used the data released by Comet Observation Database (COBS), where until November 2015 more than 1,700 visual observations of the comet PA are collected (including nearly 100 from the Polish observers). The graph maintains a regular form. Undoubtedly, this indicates the vast majority of gas tail observations. As we know, gas tails are easily recognizable because of its almost opposite direction to the Sun. It coincides with the situation shown in the diagram. Visibility of the plasma tail for most of the observation period indicates a high liquid content in the comet nucleus that sublimates rapidly during approaching closer to the Sun. This is a situation often found among the long-period comets. In the case of dust tails, we would observe a significant irregularities in the position angles. It is possible that this type of tail could be seen only at the beginning of July, which is also confirmed by photographs taken at the time.

4. CONCLUSION

In conclusion, comet C/2014 Q2 (Lovejoy) observing campaign organized by Sekcja Obserwatorów Komet PTMA and Centrum Obserwacji Komet can be marked as fully successful. Total number of 232 reports submitted to these two organizations is the best result since the outburst of 17P/Holmes in 2007. During comet's visibility in the sky, 23 observers have contributed to track its evolution over nearly 11 months. Due to using mainly visual methods of comet's observation of, we have to reckon with individual factors influencing the accuracy of the observations made by the concerned person. Our results are similar to the outcomes of other organizations coordinating observations of comets. For comparison, below is a summary of magnitude estimations made by observers from Fachgruppe Kometen and Sekcja Obserwatorów Komet PTMA:

Fachgruppe Kometen
[-inf. ; 0d]: 2.8 mag + 5 log d + 24.3 log r
[0d ; +85d]: 4.5 mag + 5 log d + 4.4 log r
[+85d ; inf.]: 3.0 mag + 5 log d + 10.3 log r

Sekcja Obserwatorów Komet PTMA
[-126d ; 0d]: 3.32 mag + 5 log d + 22.5 log r
[-36d ; 0d]: *1.38 mag + 5 log d + 37.58 log r*
[0d ; +60d]: 4.67 mag + 5 log d + 3.97 log r
[+60d ; inf.]: 4.19 mag + 5 log d + 7.8 log r

Conclusions that raised from observations obtained by Polish observers present comet C/2014 Q2 as an "wet" object, containing large deposits of ice near the outer layers of the cometary nucleus. Significant comet activity before perihelion shows extremely high emissions in that period and relatively high absolute magnitude, which means also grat albedo rate. Such object's characteristics is confirmed by the results of radio-telescope observations made by IRAM team from Sierra Nevada *(N.Biver et al.: 'Ethyl alcohol and sugar in comet C/2014 Q2 (Lovejoy)', 23 Oct. 2015).* They concluded that Comet Lovejoy was one of the most active comet that appeared in the inner solar system since the extraordinary active C/1995 O1 (Hale-Bopp). Their calculations also show high water emission, estimated to approx. 20 metric tons per second. Spanish observations were conducted during a period of the greatest activity of C/2014 Q2: 13-16 and 23-26 January 2015. The statement of an unusually high comet's activity at the time could justify the apparently overestimated results of heliocentric magnitude and activity that we have received, basing on available data from 36 days pre-perihelion. Increased activity of the comet at that time was also visible in reports of coma observations. From December to mid-February 2015, permanent coma's expansion was observed. It reached the maximum diameter of approx. 540 000 km and stabilized at approx. 480 000 km for a couple of weeks. In the result of rapid gas emission, also a significant increase in tail length was reported, with maximum value of approx. 6 000 000 km in February 2015. After that visual tail length clearly decreased. This could be also affected by increasing distance between the comet and the Earth.

C/2014 Q2 (Lovejoy) was the brightest comet in 2015. Thanks to the long period of observation and steady high brightness through about six months, it had become a very popular target for Polish observers, which classify Comet Lovejoy on 10th place of most willingly observed comets in Poland since 1985.