Rhea Occultation of HIP 74007 (SAO159034)

Analysis of Suspected Anomalous Light Curve Results

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Abstract

On 9-23-2014, an occultation of HIP 74007 by the Saturn moon Rhea was video recorded by 7 observers. A review of the light curves prompted one commenter to speculate that the event bottom of each event looked curved and that such an anomalous event characteristic might indicate that light from the occulted star diffracted or refracted around, or transmitted through Rhea. This paper reviews the light curves to assess the shape of the light curve event bottoms to see if an anomalous event occurred. Light curves were review visually. Event bottom trends were evaluated using AIC model comparison. Light curve noise levels in the baseline and event bottom data were evaluated. Light curve transitions at disappearance and reappearance were investigated. No anomalous light curve trends were found. The light curves analyzed can all be explained by the presence of normal scintillation noise in the light curve and by the simple application of a 0.2 mas stellar diameter in the occultation of the star by Rhea.

Introduction

An occultation of SAO 159034 on 9-13-2014 by the Saturn moon Rhea was observed by several IOTA amateur astronomers. Seven positive video chords were observed and reported. One independent reviewer of the data, Scotty Degenhardt, looked at the results from four of the chords and surmised he saw an 'anomalous' result in the light curves. To quote Scotty directly: "when reducing some of the Rhea occultation videos a clear trend was emerging that the occulted part of the lightcurves were not flat at all compared to the pre and post occultation part of the light curve." He saw a curved structure in each light curve as shown in the plot below.

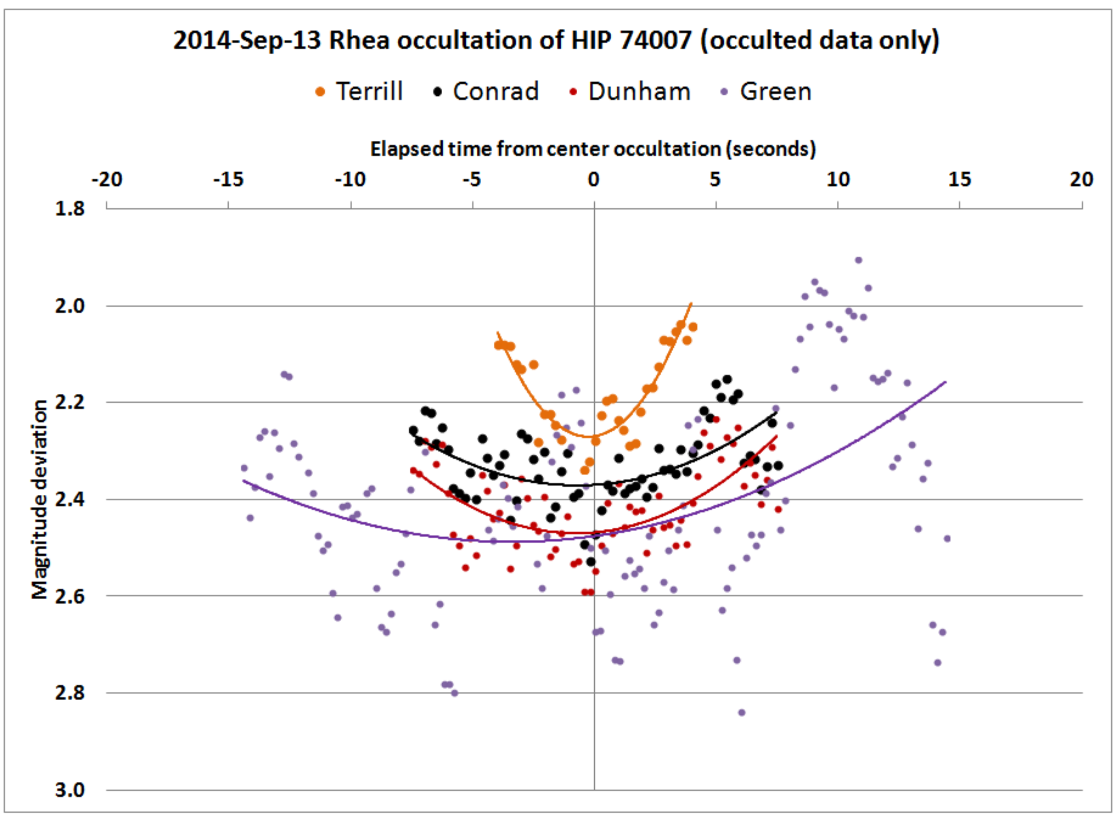

Figure 1: Scotty Degenhardt data plot

As a result of this observation Scotty Degenhardt surmised that some unusual occultation phenomenon was occurring in the light curves, such as refraction of light around Rhea, diffraction of light at the edges of Rhea, or transmission of light through Rhea. Other things that lead Scotty to conclude anomalous results were:

- “Every chord for this event had a very non flat bottom during the occultation event. “
- “I have now plotted 4 of the occulted portions of the lightcurve on top of each other and this non-flat trend is obvious. “
- “If it were stellar diameter causing this we would have seen a dimming in the occultation transition but the disappearance was instantaneous in all cases.”
- “The wing data outside the occultation has a deviation of only about 10 millimag while the deviation from a flat bottome[d] line during the occultation is about a 100 millilmag, a 10:1 S/N difference. It is not noise. And that is about all I am obligated to report in a paper.”
- “I never have to prove the cause o [sic] the non flat occultation. Presenting its occurance [sic] in four different lightcurves of the same event is valid science.”

This author pointed out that the occultation light curves might be totally consistent with natural phenomena such as normal noise encountered when measuring occultations. As a result, I undertook and independent review of the various light curves received by Brad Timerson, IOTA North American Coordinator. When available, an independent review of the original video file was also performed, providing new and independent light curves.

This report presents the findings of this independent review of the light curves.

Light Curve Data

There were 7 video chords observed and reported to Brad Timerson. The profile plot of the event showing each of the positive video chords is shown below:

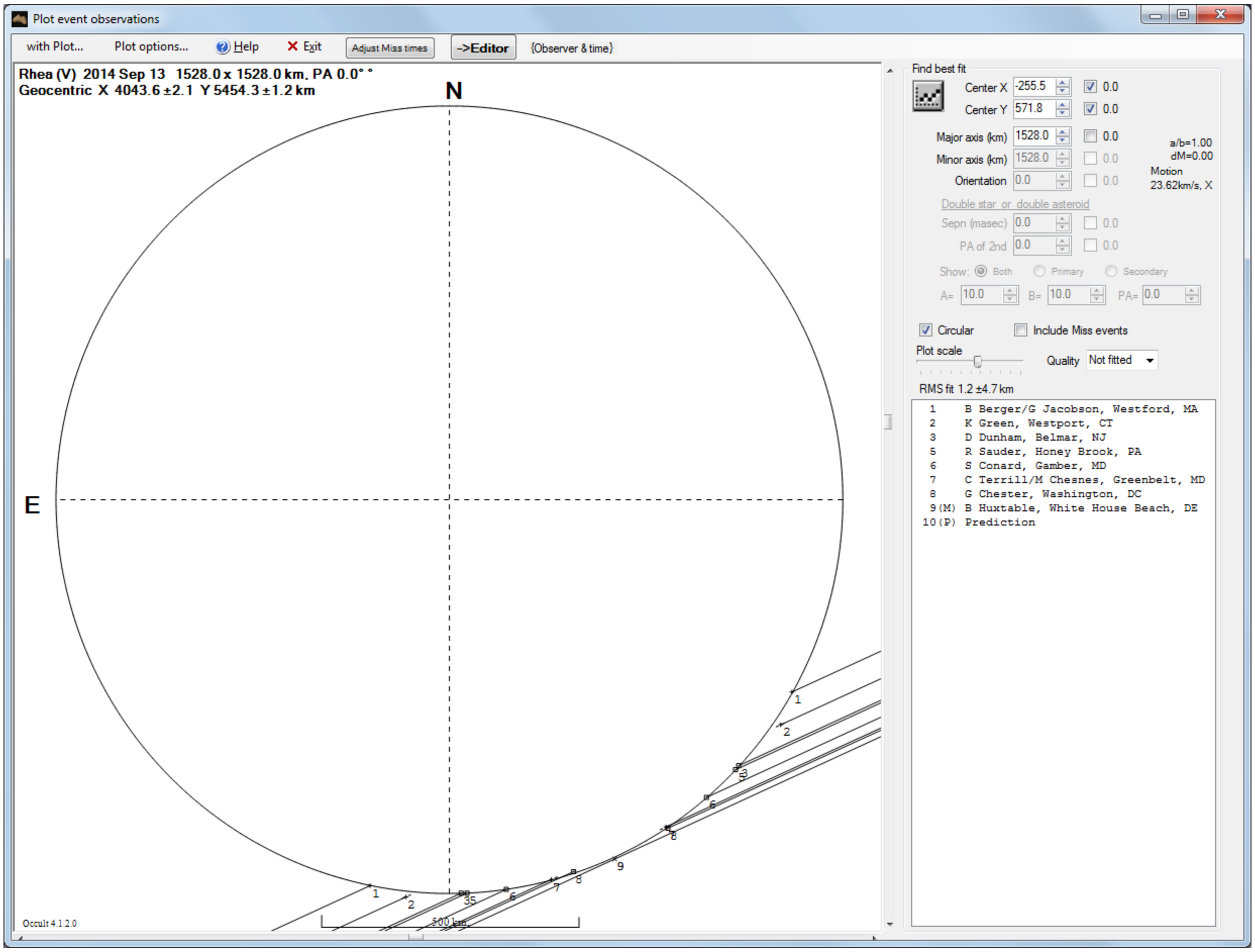

Figure 2: Occult4 Profile Plot of Video-only chords, with chord numbers and observer names

It can be seen that all the chords were near the edge of the occultation path. As a result, the limb angles are all near grazing and very shallow. Light curve data made available for this analysis included:

1 B Berger/G Jacobson, Westford, MA
2 K Green, Westport, CT
3 D Dunham, Belmar, NJ
5 R Sauder, Honey Brook, PA
6 S Conard, Gamber, MD
7 C Terrill/M Chesnes, Greenbelt, MD
8 G Chester, Washington, DC

The following is a graphical plot of each light curve in the above chord number order:

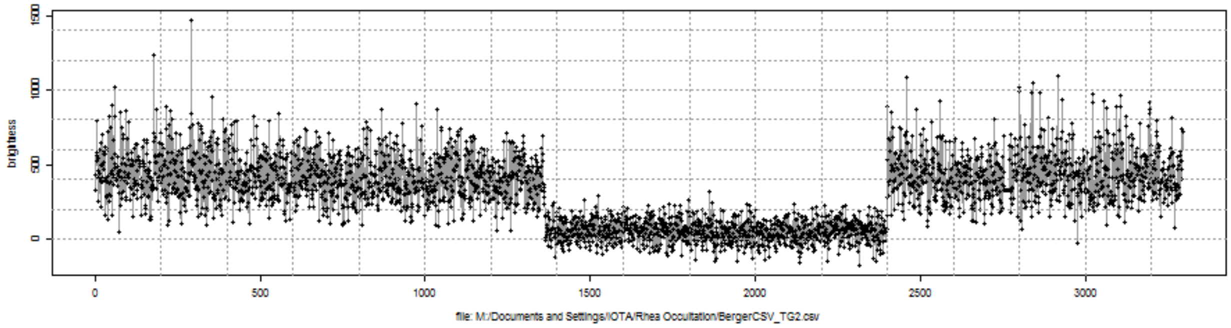

Figure 3: Chord 1 Light Curve -- Berger

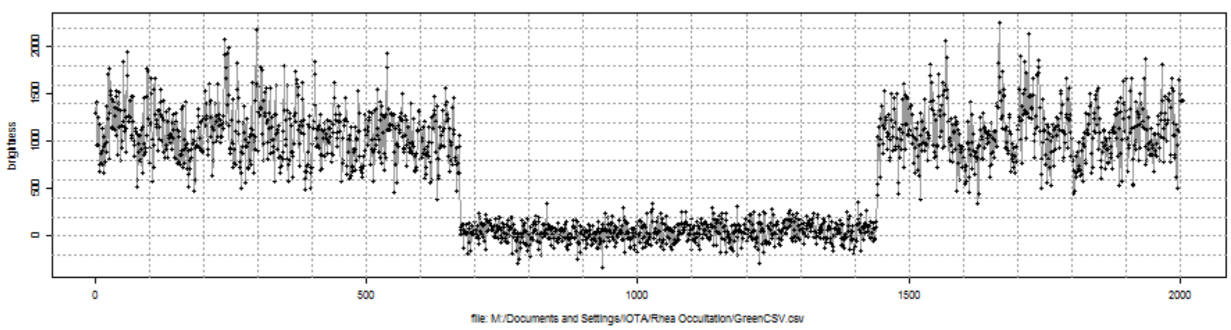

Figure 4: Chord 2 Light Curve -- Green

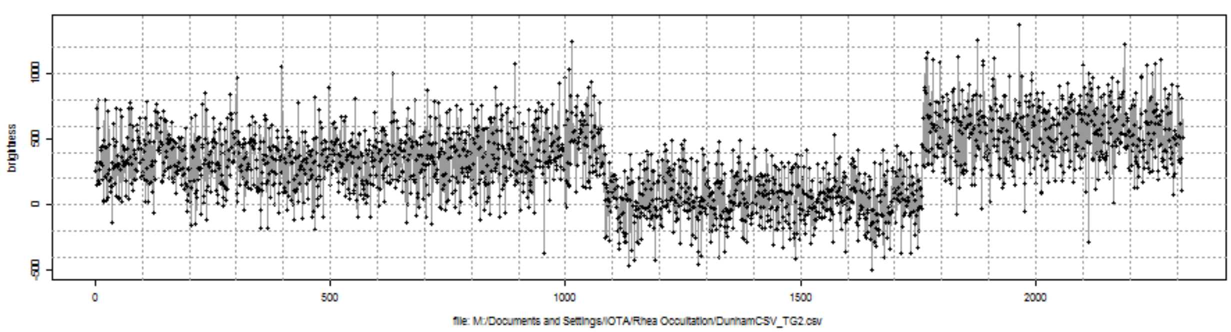

Figure 5: Chord 3 Light Curve -- Dunham

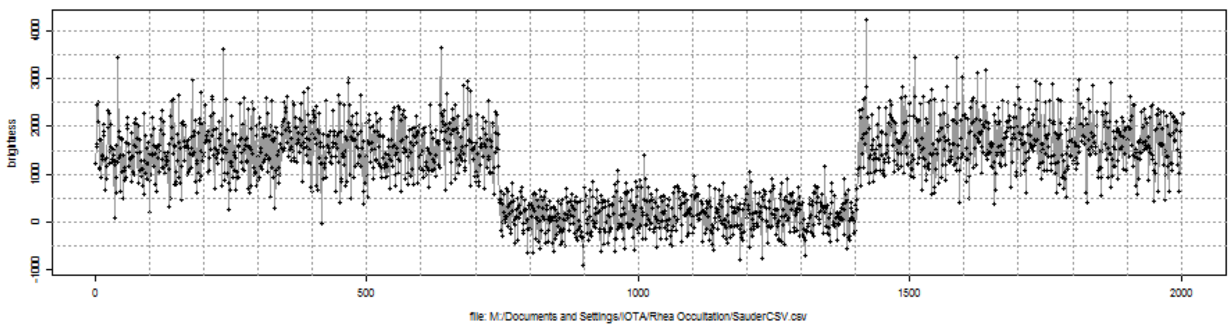

Figure 6: Chord 5 Light Curve -- Sauder

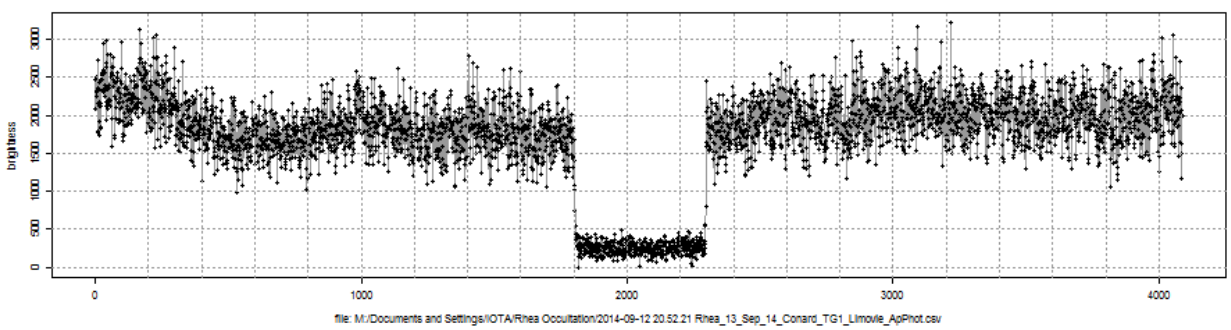

Figure 7: Chord 6 Light Curve -- Conard

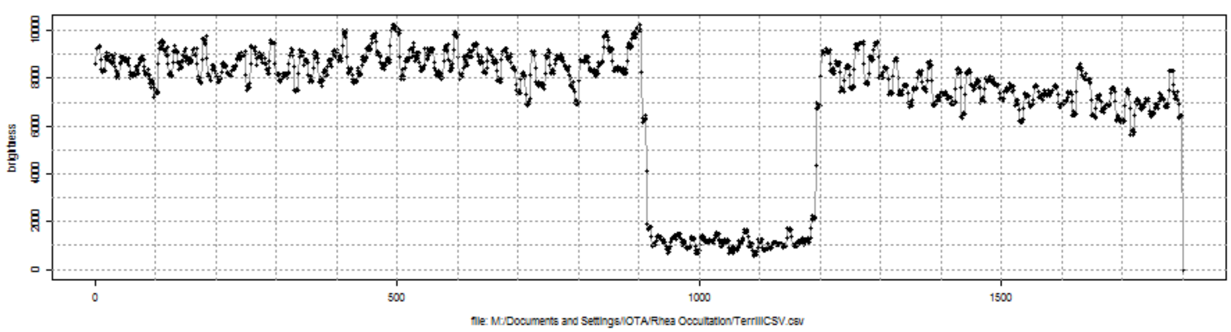

Figure 8: Chord 7 Light Curve -- Terrill

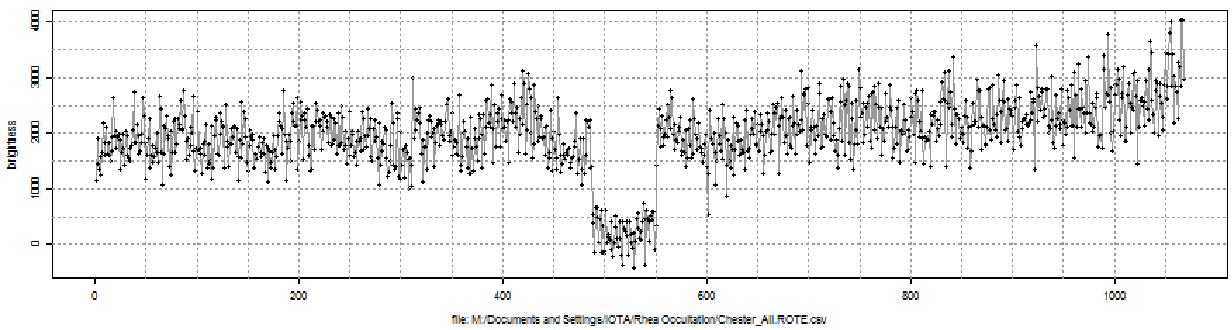

Figure 9: Chord 8 Light Curve -- Chester

An inspection of the Degenhardt plots shown in Figure 1, compared to the light curves for each chord, shown in Figures 3, 4, 5, 6, 7, 8, and 9, shows that the event bottoms of each 'event' are relatively flat, unlike the curves plotted by Degenhardt in Figure 1.

Analysis of Event Bottom Trend Lines

Bob Anderson performed a detailed analysis of each event bottom dataset. The event bottom for each chord was trimmed out of the total light curve. Each event bottom dataset was then analyzed for the best fit trend line using the Akaike Information Criterion (AIC). Each event bottom was analyzed to determine if the data best fit a flat line, a straight line, a parabola, or a 3^{rd} order polynomial equation. Two sets of AIC model relative probability comparison results were computed; the comparison of all four possible trend lines and the comparison of just a straight line to a parabola.

The four possible trend line results are shown graphically for three representative chords in Figure 10 through Figure 12. Figure 10 is representative of a chord where the third-order polynomial solution had the highest model relative probability. Figure 11 is representative of a chord where the parabola had the highest model relative probability. Figure 12 is representative of a chord where the straight line had the highest model relative probability. The AIC model relative probability results for all chords and all four modes are shown in Table 1.

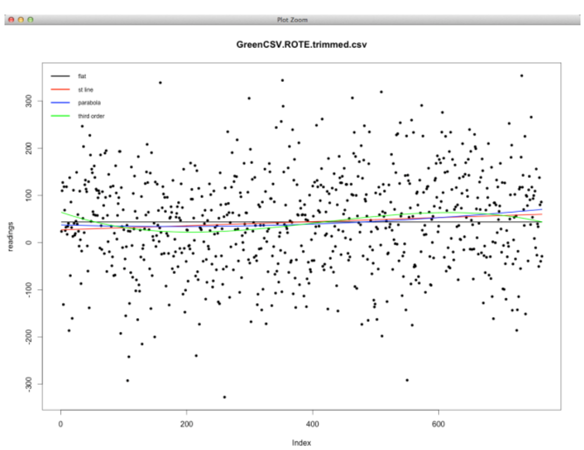

Figure 10: Multi-Trend Solution -- Green Chord 2

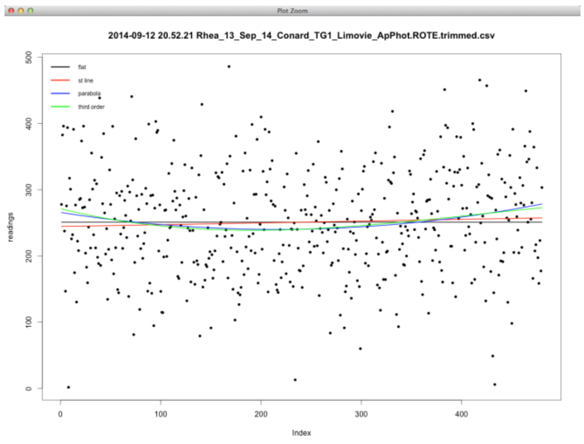

Figure 11: Multi-Trend Solution -- Conard Chord 6

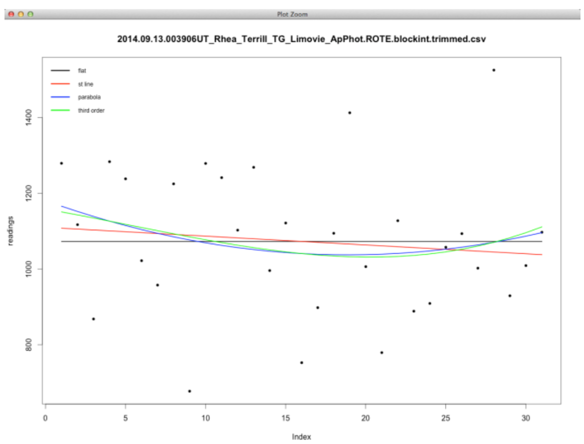

Figure 12: Multi-Trend Solution -- Terrill Chord 7

Multi-Trendline Analysis	Chord 1	Chord 2	Chord 3	Chord 5	Chord 6	Chord 7	Chord 8		Best
	Berger	Green	Dunham	Sauder	Conard	Terrill	Chester		Model
Flat Line	0	0.01	0.51	0.42	0.09	0.63	0.16		3
Straight Line	0.36	0.07	0.2	0.34	0.06	0.24	0.08		0
Parabola	0.23	0.05	0.13	0.14	0.6	0.1	0.52		2
Third Order Polynomial	0.41	0.87	0.16	0.11	0.26	0.03	0.24		2

Table 1: AIC Model Relative Probability -- Flat Line, Straight Line, Parabola, and Third Order Polynomial

The event bottom trend line analysis was performed using raw data except the data was block-integrated where the video is integrated.

Reviewing the results in Table 1, no clear ‘trend’ appears. For three chords, the flat line has the highest relative model probability. For two chords, the parabola has the highest relative model probability, and for two others, the third order polynomial has the highest relative model probability. If we just look at straight trend versus curved trend, there are three chords where straight is preferred and 4 where curved is preferred.

Because of the close similarity of the flat model to the straight-line model and the parabola to the third order model, the AIC analysis was reapplied with only two model options: straight line and parabola. The resulting graphical solutions are shown in Figure 13 through Figure 19. The AIC model relative probability results for all chords and the two models are shown in Table 2.

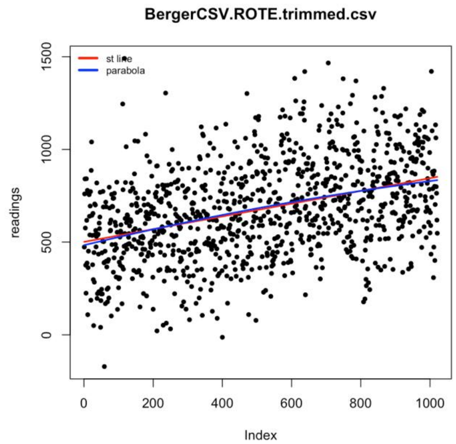

Figure 13: Straight Line Versus Parabola Solution -- Berger Chord 1

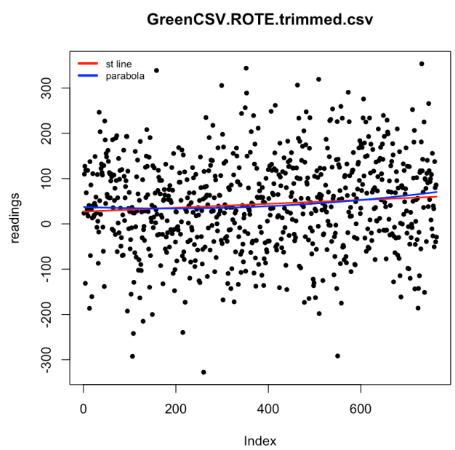

Figure 14: Straight Line Versus Parabola Solution -- Green Chord 2

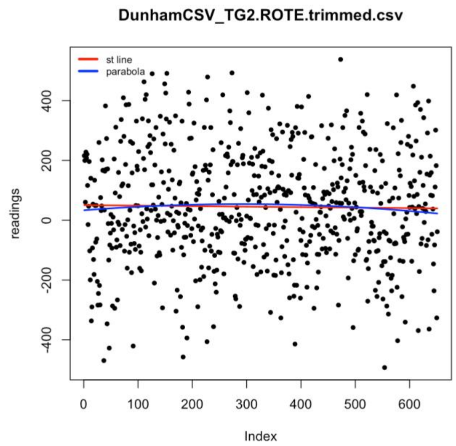

Figure 15: Straight Line Versus Parabola Solution -- Dunham Chord 3

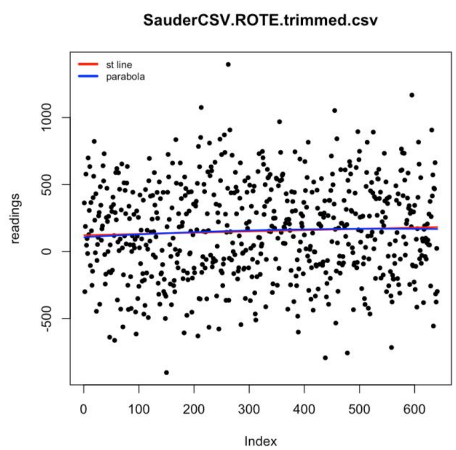

Figure 16: Straight Line Versus Parabola Solution -- Sauder Chord 5

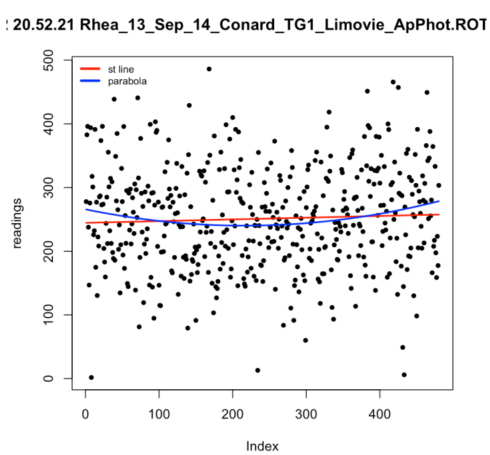

Figure 17: Straight Line Versus Parabola Solution -- Conard Chord 6

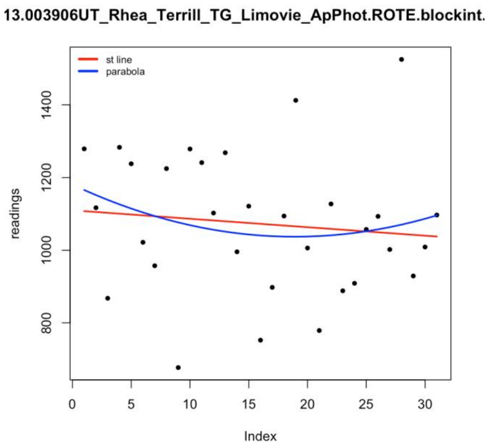

Figure 18: Straight Line Versus Parabola Solution -- Terrill Chord 7

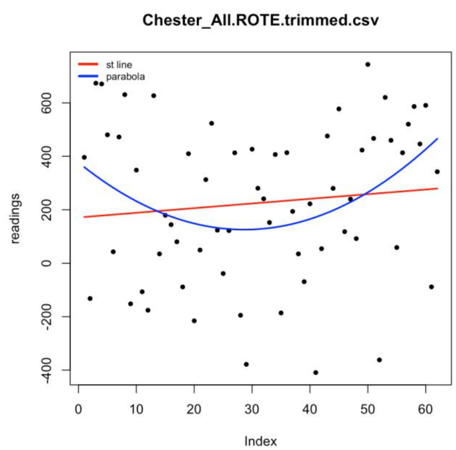

Figure 19: Straight Line Versus Parabola Solution -- Chester Chord 8

Straight Line vs Parabola	Chord 1	Chord 2	Chord 3	Chord 5	Chord 6	Chord 7	Chord 8		Best
Trendline Analysis	Berger	Green	Dunham	Sauder	Conard	Terrill	Chester		Model
Straight Line	0.61	0.55	0.62	0.71	0.09	0.7	0.13		5
Parabola	0.39	0.45	0.38	0.29	0.91	0.3	0.87		2

Table 2: AIC Model Relative Probability -- Straight-line versus Parabola

Reviewing the results in Table 2, the straight line model has the highest model relative probability in 5 of the 7 chords, indicating a clear preference for a straight line solution to the event bottom data. However, two chords, Chord 6 and Chord 8 have a very high model relative probabilities for a curved solution. As these chords are close to the edge of Rhea compared to Chords 1-5, this might be considered proof of Scotty Degenhardt's claim of anomalous light curve results. Chord 7, Terrill, however is between Chords 6 and 8 and Chord 7 has a high model relative probability for a straight line. If a curved event bottom trend line is caused by a physical phenomena on the limb of Rhea, it seems Chord 7 should have the same effect. It doesn't. Therefore, Scotty Degenhardt's claim is not proven.

A review of the light curves for Chord 6 and 8 (Figure 7and Figure 9) shows considerable variation of the baseline light curve. A supplemental analysis of Chord 6 was performed to determine if the baseline variation could be a cause of similar variation in the event bottom data. Chord 6 data included a light curve for a second field star. The field star had very similar baseline light curve variations as did the target star (Rhea + star). This is an indication of outside factors such as clouds or haze affecting the data. A comparison of the two light curves – target star and field star – are shown in Figure 20.

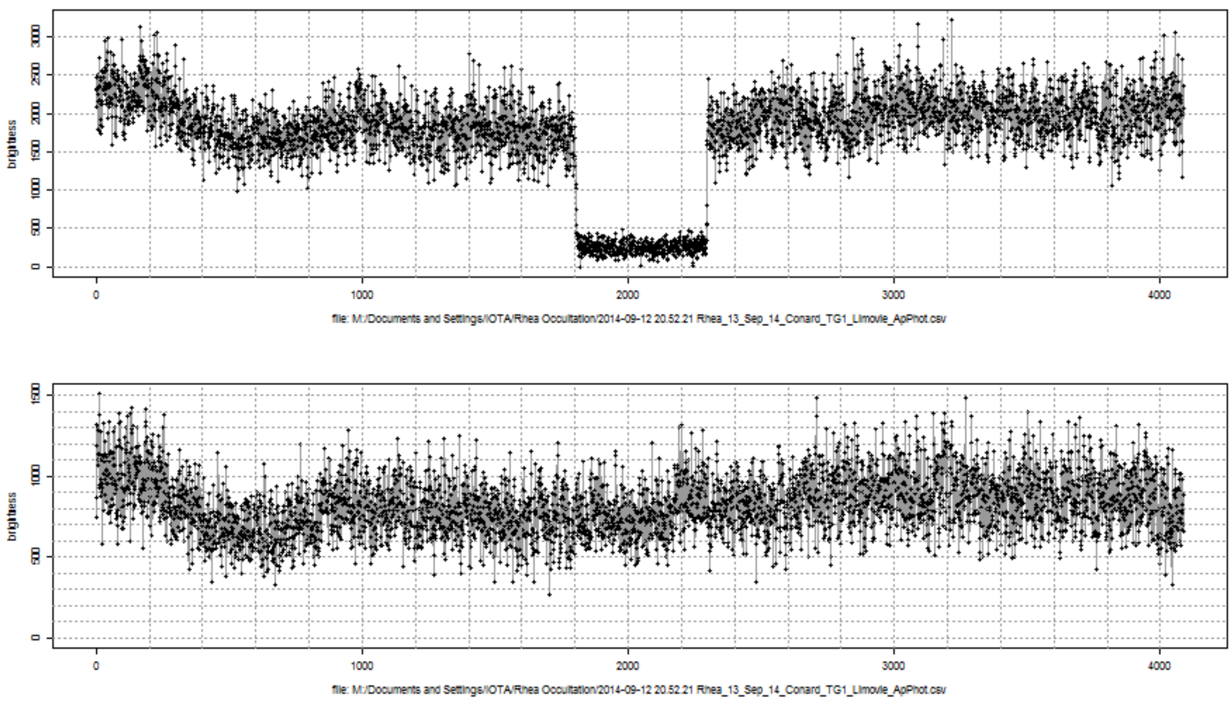

Figure 20: Conard Chord 6 target star and secondary star light curves

The target star light curve was normalized using the light curve of the second field star. The normalized light curve was analyzed for a trend line in the event bottom data. The results are shown in Table 3. Once outside effects are eliminated from the light curve, the AIC analysis finds the straight line trend to have the highest model relative probability. The results are entirely reversed.

Conard Normalized to Secondary Star	
Straight Line	0.71
Parabola	0.29

Table 3: Conard AIC Model Relative Probability -- Afer Light Curve Normalized to Secondary Star

A similar check of the Chord 8 data could not be performed as no video for this chord was received for review and no second star is included in the light curve data. Never-the-less, Figure 9 shows considerable variation in the baseline light curve prior to and after the event. It seem logical that variations due to scintillation or other effects are also occurring in the event bottom data. For example, a plot of the light curve just before and just after the event shows a distinct change in brightness of the target (Rhea + star). This jump in brightness is graphed as a straight red line in Figure 21.

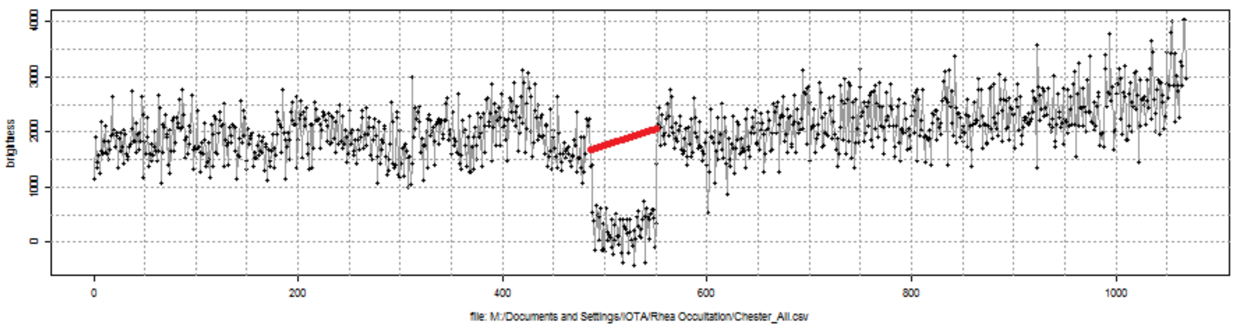

Figure 21: Chester Chord 8 brightness discontinuity across event

If we presume that such a brightness change must be also affecting the data in the event bottom, then it is reasonable to conclude that Chord 8 may erroneously show a curved trend line.

Light Curve Noise Analysis

Scotty Degenhardt stated the baseline noise was exceeded by the event bottom noise by a ratio of 10:1. The actual statement is: “The wing data outside the occultation has a deviation of only about 10 millimag while the deviation from a flat bottome[d] [sic] line during the occultation is about a 100 millilmag, a 10:1 S/N difference. It is not noise.” In this statement, this author interprets the phrase: ‘wing data deviation’ as the baseline noise 1-sigma noise level; and, ‘flat bottom deviation’ as the event bottom noise 1-sigma noise level. Also this author assumes that “10:1 S/N difference” refers to a 10:1 ratio between baseline noise and event bottom noise.

R-OTE[i] was used to analyze each light curve. The noise for each light curve was characterized by a ‘noise sigma’ value. Noise sigma is the 1-sigma level of the readings about the mean value of the readings as measured in absolute brightness values. If a noise sigma is greater than another noise sigma, then the variations about the mean value are greater for the larger noise sigma.

The following Table 4 is a table of noise sigma values for the baseline brightness (before and after the event); this is called Bnoise; and, the event bottom brightness (during the event); this is called Anoise. The ratio of the two noise sigma values is computed as Bnoise/Anoise.

It can be seen in the table that Bnoise is greater than Anoise by approximately a factor of 2, instead of Anoise being greater than Bnoise by a factor of 10 as claimed by Scotty Degenhardt. Lower noise during an event is typical and expected, based on the analysis of hundreds of light curves. The noise levels in the light curves are not anomalous.

Rhea Noise Comparison:				
Chord	Observer	Bnoise	Anoise	Bnoise/Anoise
1	Berger	160.54	74.99	2.14
2	Green	292.00	102.23	2.86
3	Dunham	237.24	187.29	1.27
5	Sauder	551.77	352.66	1.56
6	Conard	211.55	57.05	3.71
7	Terrill	588.52	191.90	3.07
8	Chester	424.74	294.40	1.44

where: Bnoise = baseline noise prior to and after the occultation
Anoise = event bottom noise during the event

Table 4: Table of noise sigma values for all chords

Analysis of Light Curve Transitions

Scotty Degenhardt stated that all transitions in the light curve data were ‘instantaneous in all cases’ and therefore precluded the possibility of stellar diameter being even a partial cause of any anomalous brightness changes at the beginning and end of each event bottom. This author also reviewed the light curves and found the following results.

Four light curves had high enough SNR ratios to allow the observation of any stellar diameter effects on the transition light curve. These were Green (Chord 2), Conard (Chord 6), Terrill (Chord 7), and Chester (Chord 8). These can be seen in Figures 4, 7, 8, and 9. Each of these light curves were analyzed for SNR. The results are shown in Table 5.

Signal-to-Noise Ratio Analysis

In R-OTE, SNR (signal to noise ratio) is defined as:
SNR = I(star)/Bnoise
where:
I(star) = B - A
B = baseline intensity (I(star) + I(ast)
A = event bottom intensity (I(ast))
Bnoise = the 1-sigma noise noise level of B

Chord	Observer	SNR
1	Berger	2.33
2	Green	3.58
3	Dunham	2.30
5	Sauder	2.74
6	Conard	6.67
7	Terrill	12.10
8	Chester	4.36

Table 5: SNR analysis results

For Chord 6: Conard and Chord 7: Terrill, the transitions show one or more frames (or block of integrated frames) in each transition. The D (disappearance) for Conard and the R (reappearance) for Terrrill transitions are highly magnified as shown in Figure 22:

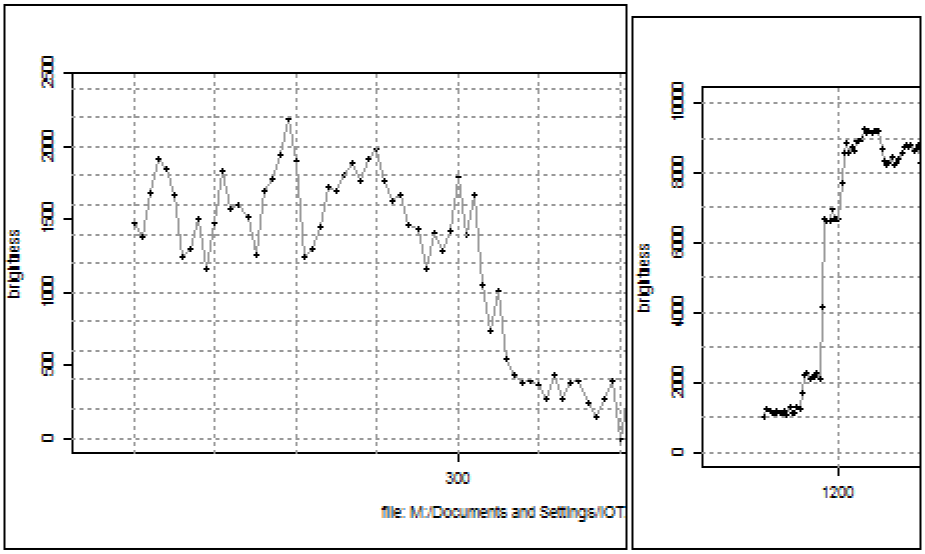

Figure 22: Magnified transitions for Chord 6 D (left) and Chord 7 R (right)

In this instance, the star, HIP 74007 is listed in Occult4 as having a non-point size, as shown in Figure 23. The expected magnitude drop for the event was 2.5. Therefore, gradual transitions would be either expected or at least unsurprising in the Rhea event light curves.

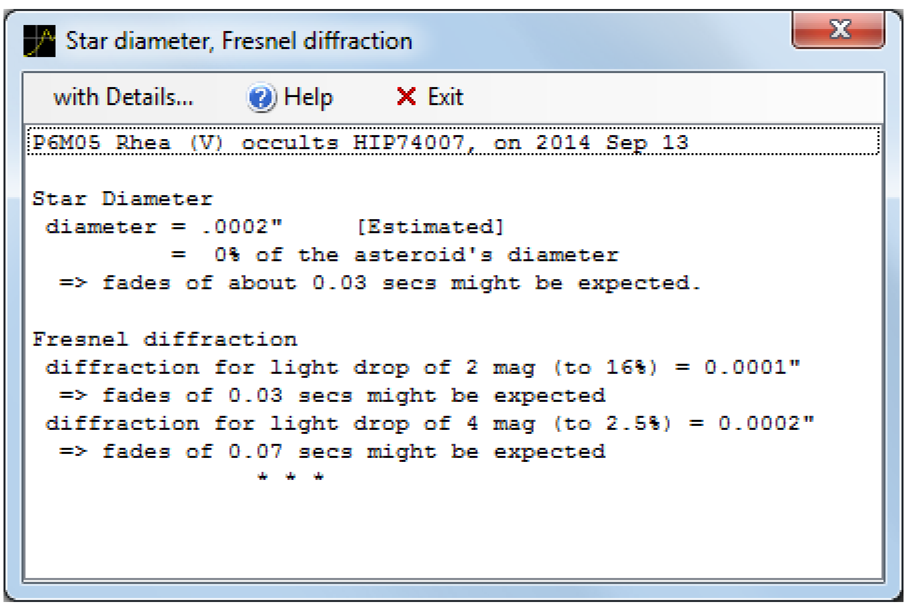

Figure 23: Star diameter properties from Occult4

Both light curves were analyzed in R-OTE for the fit to an Edge-on-disk (EOD) model, the gradual transition caused by a star of non-point size. A valid EOD solution was found (see Figure 24).

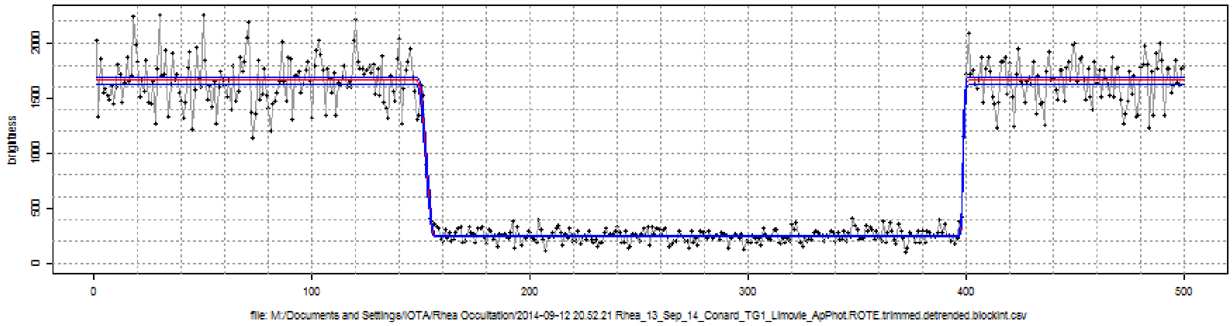

Figure 24: Chord 6 EOD solution

The EOD solution was compared to a Square Wave solution using Akaike Information Criterion. The results indicate that an EOD solution is preferred – 99.9% for EOD solution compared to 0.001% for Square Wave solution.

Calculate model probabilities

```
Square wave model probability = 0.000011

Edge on disk model probability = 0.999989
```

Figure 25: R-OTE EOD to Square Wave AIC comparison statistics

Using the 0.2 mas star size listed in Occult4, the limb angles of the Chord 6 light curve were calculated and plotted in R-OTE. The results are as follows:

```
Given: star diameter (mas) = 0.20 (+0.05 -0.05)
 with: delta.D.err = 0.375
  and: delta.R.err = 0.190

star diam (mas)     = 0.20 (+0.05 -0.05)
thetaD(degrees)     = 82.68 (+2.12 -2.38)
thetaR(degrees)     = 65.65 (+7.87 -10.14)
```

Resulting limb angles are shown in Figure 26.

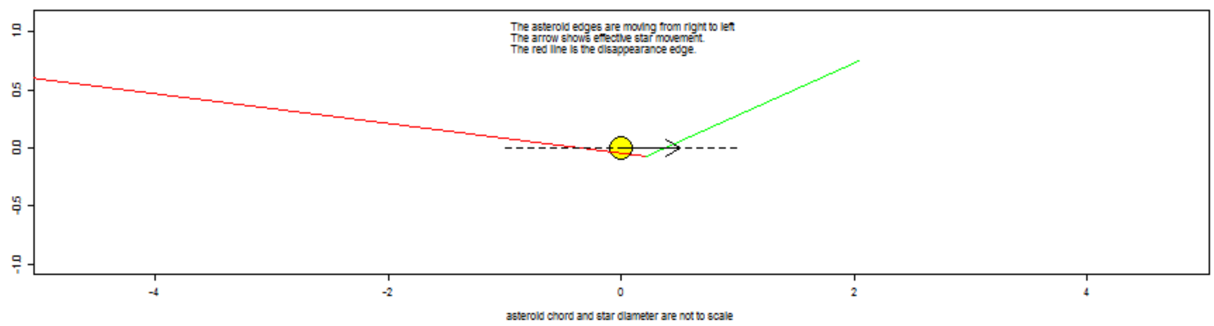

Figure 26: Limb angles for Chord 6 based on 0.2 mas stellar diameter

These limb angles compare favorably to the limb angles shown in the Occult4 ellipse of best fit to the chords as shown in Figure 27. A similar analysis was performed for the Terrill and Chester data (Chords 7 and 8), and similar or better comparable limb angles were obtained.

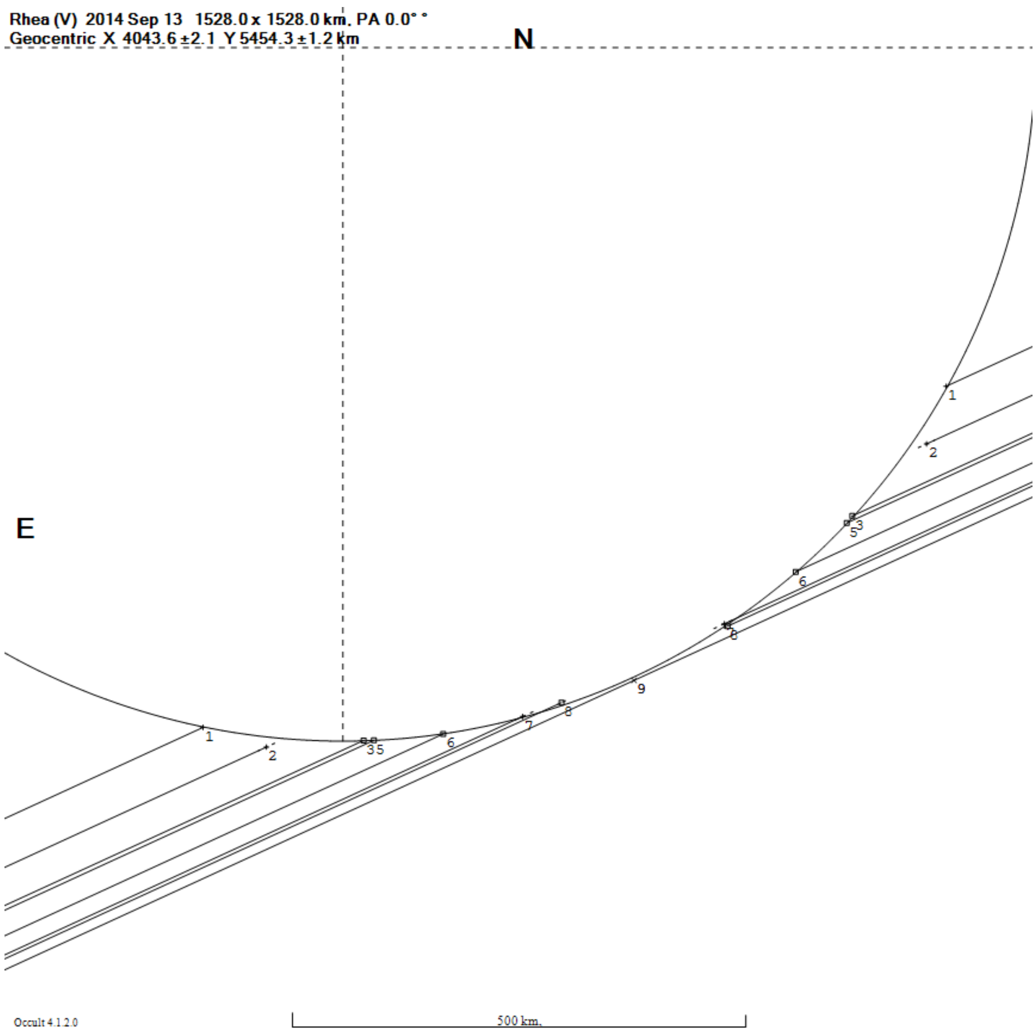

Figure 27: Occult4 Profile plot of occultation results

Based on the R-OTE EOD analysis, there are gradual transitions in the data, the gradual transitions fit and EOD model in preference to an ‘instantaneous’ square wave model, and the limb angles derived from a 0.2 mas star are a reasonable fit to the actual chord limb angles shown in the Occult4 profile.

Discussion of Scotty Degenhardt Anomalous Light Curve Statements and Conclusions about Anomalous Light Curves

Scotty Degenhardt made several statements about the anomalous nature of the light curves acquired by observers on the Rhea occultation. Each statement will be reviewed and discussed in light of the analysis results presented in this paper.

“Every chord for this event had a very non flat bottom during the occultation event. “ “I have now plotted 4 of the occulted portions of the lightcurve on top of each other and this non-flat trend is obvious. “

A visual inspection of the brightness light curves provided by the observers or derived from the videos for each chord clearly shows each light curve to have an essentially flat bottom with little or no curvature. Each of the chord light curves shows variable amounts of variation in brightness, both in the baseline and in the event bottom data. It does not appear, based on visual inspection, that the Degenhardt premise; event bottom light curves are ‘anomalous’; is valid. Most certainly, Degenhardt’s light curve attributed to Chord 7 (Terrill) does not look anything like the actual light curve shown in Figure 8.

A supplemental study of event bottom data trend lines showed that a straight line model has a higher model relative probability than a curved line in 5 out of 7 chords. Of the two chords that showed a curved trend line, one (Conard Chord 6), when the light curve was normalized to a nearby secondary field star, showed higher model relative probability for a straight line. The other chord, Chester Chord 8, also showed significant variation in the baseline light curve. It can be surmised that similar variations could be affecting the event bottom data, which could mimic a curved trendline.

One noteworthy difference between the Degenhardt plots and the original light curve plots for each chord – Degenhardt plotted his results normalized to magnitudes and to elapsed time from centerline in seconds. Both normalizations, to some degree, alter the original data. Magnitudes are exponential (logarithmic) values, while the original data is not. The use of logarithmic values in the plotting of the data may distort minor variations in brightness. The use of different cameras with associated different gamma characteristics in the light curve output may also distort minor variations in brightness when measured logarithmically.

“If it were stellar diameter causing this we would have seen a dimming in the occultation transition but the disappearance was instantaneous in all cases.”

Gradual dimming was in fact seen in 4 of the 7 chords analyzed. An analysis of EOD (gradual transition) model for three of the chords indicates a statistically significant preference over the Square Wave (instantaneous) solution preferred by Scotty. The star HIP 74007 is known to have a finite angular size, estimated at 0.2 mas. Using the transition light curve data, R-OTE analysis fits reasonable limb angles, equivalent to the measured profile using all chords and the published 0.2 mas stellar diameter.

"The wing data outside the occultation has a deviation of only about 10 millimag while the deviation from a flat bottome[d] line during the occultation is about a 100 millilmag, a 10:1 S/N difference."

The analysis of noise in the paper, using the original brightness data (not magnitude differences as used by Degenhardt) shows an exactly opposite conclusion from that concluded by Scotty Degenhardt. All baseline noise has a higher noise sigma than the event bottom data, as shown in Figure 10. The ratio between baseline noise and event bottom noise is approximately 2:1 with baseline noise higher.

"I never have to prove the cause o [sic] the non flat occultation. Presenting its occurance [sic] in four different lightcurves of the same event is valid science.

This author finds the Degenhardt analysis of Rhea data was biased by first assuming a curved event bottom relationship and rejecting a finite star size alternative, without checking these assumptions. While Scotty Degenhardt did not have to prove a cause of a non-flat occultation, he did have to prove the occultations were non-flat before proceeding on to looking at exotic alternatives for the cause of an effect that does not appear in the data. This author believes that all light curve results are easily explained by a simple series of near grazing occultations of a star of finite size by an airless occulting body of large size. No exotic alternative solutions are required. The principle of 'Occam's razor' would favor the selection of the simplest, proven, and obvious alternative(s), rather than more exotic and unproven alternatives.

Conclusion

I conclude the initial premise made by Scotty Degenhardt that the Rhea light curves show anomalous curved event bottoms is incorrect. The source of the curvature noted by Scotty is unknown. The light curves analyzed can all be explained by the presence of normal scintillation noise in the light curve and by the simple application of a 0.2 mas stellar diameter in the occultation of the star by Rhea.

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[i] R-OTE (R-Code Occultation Timing Extractor), written by Bob Anderson. The full program release package, including: R-code program modules, Read-Me file, and User Manual for the program are available at: http://www.asteroidoccultation.com/observations/NA/R-OTE_3.8.5.R%20Release%20Package.zip