Amateurs Observe WD 1145+017

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Amateurs have made a significant contribution to the understanding of how white dwarf stars cause planets and asteroids in close orbits to disintegrate and produce dust clouds that cause observable transit fade events, near-IR excess debris disks and metal gas cloud absorption lines. A double ring system of dust and gas, respectively, is an emerging account for these amateur and other professional observations. WD1145 is showing us what our solar system will be like for most of its existence. It is possible that this white dwarf is oriented with such a favorable inclination that it can serve as a "Rosetta Stone" for understanding all white dwarfs, which most stars will become. As someone might remark after reading this paper "Gee, I didn't know amateurs were better able to do something than the pros, and use that unique capability to help solve a puzzle in the sky."

Background

At the center of our sun protons collide at high speed and sometimes form a helium nucleus (proton and neutron pairs), with leftover energy in the form of photons of light. After millions of years these photons reach the sun's surface and escape as sunlight. Stars like our sun can only do this for about 10 billion years before the center is depleted of hydrogen. When this happens our sun begins a complicated process leading to a swelling in size to the orbit of Venus, and a loss of almost half its mass. It will be cooler, and resemble what we call a "red giant." After this expansion comes a collapse to the size of the Earth. With a mass ~ 60% of the original value, and a diameter slightly larger than the Earth, a cubic inch of the sun would will 8 tons. The sun will have become a "white dwarf." Most stars will end up as white dwarfs. Our sun is halfway there, so after it becomes a white dwarf in about 5 billion years it will remain one for tens of billions of years. In other words, most of our sun's existence will be as a white dwarf.

What about the Earth and the other planets of our solar system. Mercury and Venus will certainly be swallowed-up by the sun during its expansion to a red giant. The Earth will be vaporized to nothing but possibly a residual core before the sun begins its collapse. Mars and the outer planets will mostly remain intact. So most of the solar system of planets and asteroids will remain orbiting our diminutive white dwarf sun. And this is the overall picture of what our solar system will be like for most of its existence.

But there are details, interesting details to this picture which we're just now learning. And one of the most unexpected things about these details is that amateur observations are contributing to their discovery.

An early clue about white dwarfs and any remaining planet system came when it was noticed that almost half of white dwarfs have a spectrum with absorption lines produced by metal atoms such as iron, calcium, nickel, etc. These atoms sink fast into a white dwarf atmosphere, so there must be a somewhat continuous accumulation of them. It was suspected for decades that leftover planets and asteroids were producing these metals in the form of dust slowly raining down on their little star. But that would require that the planets and asteroids were disintegrating, and if that was happening what was the process, and how could it be verified by observations?

Kepler Discovery

Enter *Kepler*, the "little spacecraft that could!" After two of its four reaction wheels failed, the *Kepler* mission was changed to observing the ecliptic because those observations could use a configuration in which the solar wind substituted for one of the reaction wheels. The *Kepler* K2 mission included the star WD 1145+017, hereafter referred to as WD1145. It had been known that WD1145 had a debris disk because it was brighter than a blackbody at near-IR wavelengths (3.4 and 4.6 micron). A debris disk is usually associated with star systems just forming, so it's unusual for a white dwarf to have one. It was also known that WD1145 had metal absorption lines. So, even before the *Kepler* mission this star had gained the interest of astronomers specializing in white dwarfs.

The *Kepler* K2 mission revealed that WD1145 exhibited fades at regular intervals (Vanderburg et al, 2016). The fades were small, typically 1%, and a periodicity analysis revealed 6 distinct periods, ranging from 4.5 to 4.9 hours. Since this particular set of *Kepler* observations was made with exposure times of 30 minutes, it was not known if the fades had structure shorter than 30 minutes, with depths greater than 1%. But combining the facts that there were fades, presumably caused by dust clouds in orbit, and that WD1145 had metal absorption lines, and it had a debris disk, made WD1145 the first candidate for testing the idea that planets were disintegrating in a way that caused all three observational anomalies.

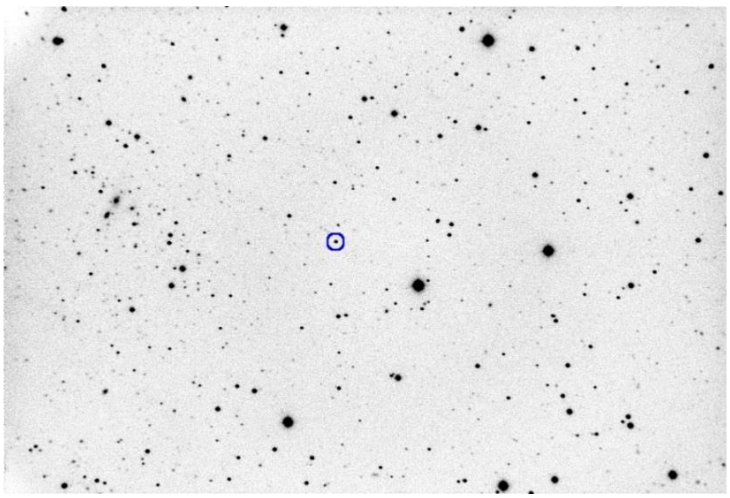

Figure 1. *WD1145 is at 11:48:33.59 +01:28:59.3 (J2000). FOV = 27 x 18 'arc, northeast at upper left. Imaged with a 14" telescope for a total exposure time of ~ 5 minutes.*

Before announcing these results to the "public domain" the professional astronomers observed WD1145 with ground-based telescopes. They found a few isolated fades, lasting for much shorter times and being much deeper than observed by *Kepler*, but the overall level of fade activity was modest and compatible with what *Kepler* observed.

Amateur Observations Begin

The publication of these results occurred in October, 2015. As soon as I learned about WD1145, I began to observe it with my backyard observatory. It was a difficult target, being very blue and faint, with V-mag ~ 17.3; but the most difficult part was having to observe it at low elevation for only a couple hours before sunrise. I like observing challenges and was ready to figure out ways to measure those fade features the pro's had written about. Eventually I was able to achieve a SNR of ~ 15 using 60-second exposures with my Meade 14" Schmidt-Cassegrain telescope and SBIG ST-10XME CCD. I was surprised to see a deep fade on my second observing attempt, and another on the next observing date. Soon it was evident that the fade activity for WD1145 was much greater than shown by previous observations. This is the first contribution by amateur observers to our growing understanding of WD1145.

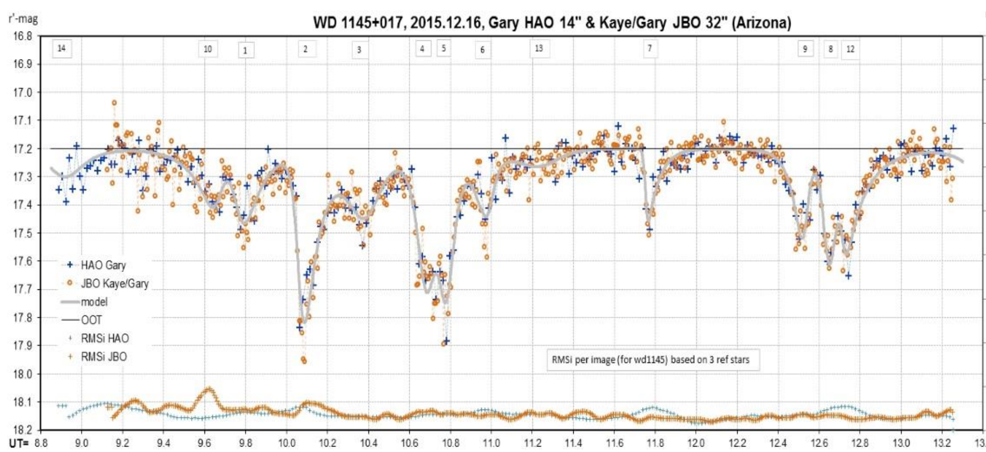

Figure 2. *Example of early light curves using two amateur backyard observatories, consisting of 14" and 32" telescopes (exposure times are 60 and 15 seconds). Thirteen fade features are evident in both light curves. The 4.5-hour coverage is exactly one full orbit of the dust clouds. Data is for December 16, 2015.*

After a couple weeks of seeing amazing fade events I began inviting other amateurs with advanced observing skills to join me on this new, exciting project. Our final team of four amateur observers were B. Gary (14", Arizona), T. Kaye (32", Arizona), P. Benni (14", Boston, MA) and J. Foote (16", Utah); we produced light curves at an average rate of one for every 1.5 days for the next 2.5 months, for a total of 186 observing hours. This coverage was unprecedented, and it would have been prohibitively expensive for professionals using professional telescopes to duplicate it.

Timescales for Changes – An Aside

Before proceeding with a chronology of events, I want to illustrate something important about WD1145 dip behavior, and this will require showing data taken several months later than where we are in the story. Figure 3 shows a single light curve that is longer than the dust cloud orbit period of 4.5 hours. It shows that in one orbit of 4.5 hours a dust cloud's dip pattern doesn't change much.

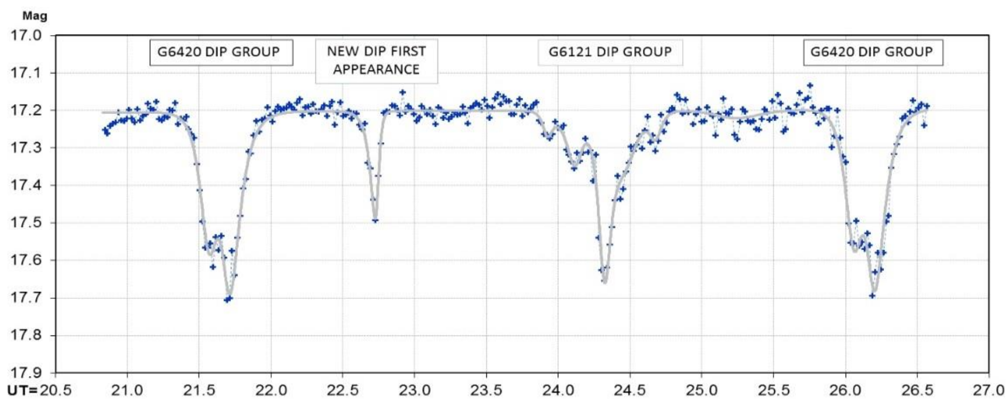

Figure 3. *Light curve for 2016 April 26 (by R. Alonso, using a 32" telescope). The observing session was 5.6 hours long, or 1.3 orbits for the dust clouds. The dip structure at 21.5 UT repeats at 26.0 UT (4.5 hours later). Only slight changes occurred during this one orbit of the dust cloud.*

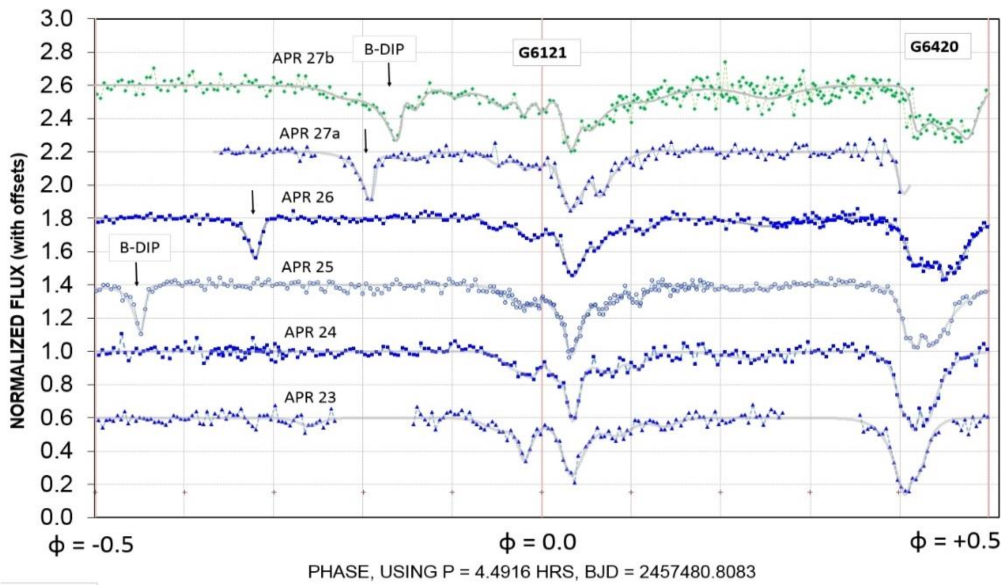

Figure 4. *Waterfall plot of phase-folded light curves during a 5-day interval in 2016, using an ephemeris that keeps the main group of dips at approximately phase zero.*

Figure 4 is a set of five light curves taken one day apart, plus one taken a few hours later. Notice that the dip structure changes slowly for a daily timescale. For now, ignore the fast-drifting B-dip feature.

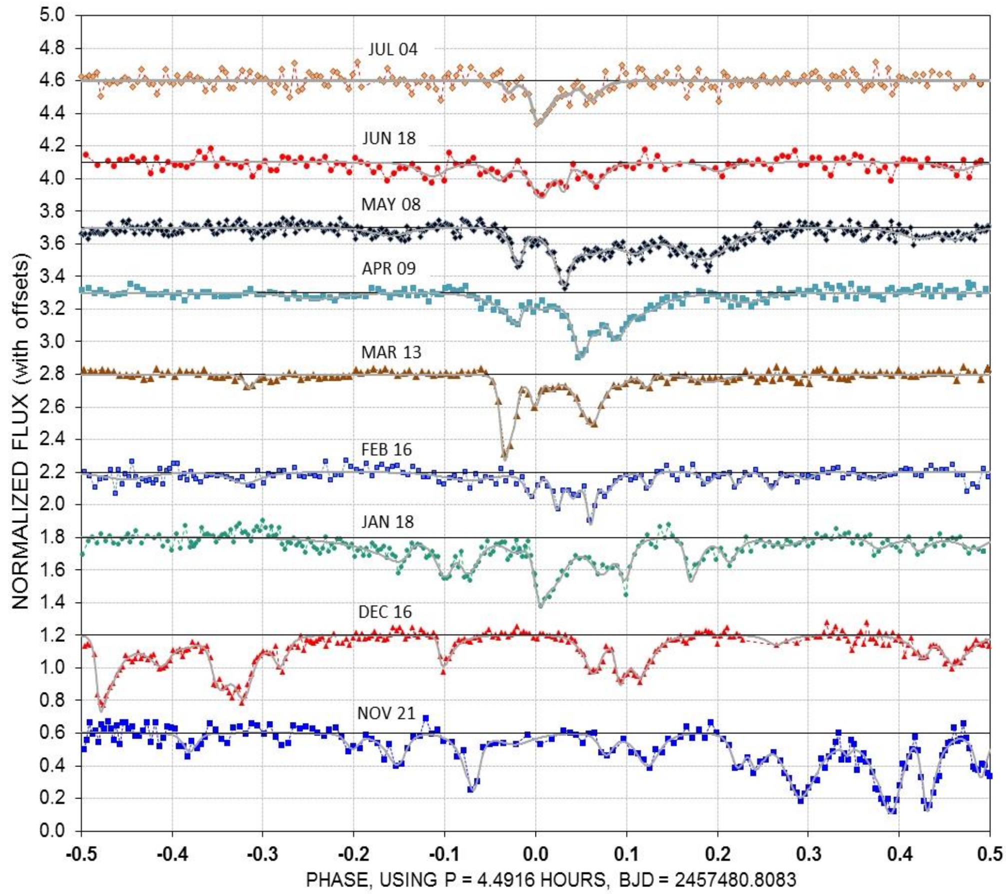

Figure 5. *Samples of light curves taken at monthly intervals (all data are from amateur backyard observatories; six made with a 14" telescope, one is a combination of data with 14" and 16" telescopes, and two are combined data from 14" and 32" telescopes).*

Figure 5 illustrates that on a month timescale the dip patterns change so much that no individual dip feature can be identified with another, using only sample light curves at monthly intervals.

The purpose in showing these last three figures is to illustrate the importance of having a high density of observational coverage, such as daily or once every other day, if an investigation of individual dip features is to be performed. This is a task for which amateurs are ideally suited, such as a team of four or five amateurs. Professional observations lasting all night on a daily basis can be prohibitively expensive.

Amateur Observing Story Resumes

Now let's return to the story of how things happened, resuming with early December, 2015. After only three weeks of observing it was apparent that the fade events, which professionals call "dips," were occurring at times that were earlier each night than had been expected based on the *Kepler* main periodicity of 4.500 hours, referred to as the A-period. To understand what is meant by "drifting dips" consider a "waterfall diagram" (suggested by amateur observer TK), which is a plot of dip phase versus date for all dips in an archive of many dates. Phase can be defined using a period that is adopted as corresponding to the asteroid producing the dust clouds. Our analysis adopted the *Kepler* data's most prominent period, the A-period = 4.500 hr. We expected to see most dips occurring at the zero phase region, provided we could estimate a date when the A-asteroid was in front of the white dwarf. The K2 A-period ephemeris wasn't accurate enough for extrapolating the 1.5 years ahead to our observing dates, so we arbitrarily adopted a date that corresponded to placement of the most impressive dips we were observing at zero phase. Fig. 6 is the waterfall diagram that we constructed from a 2.5-month set of amateur light curve data.

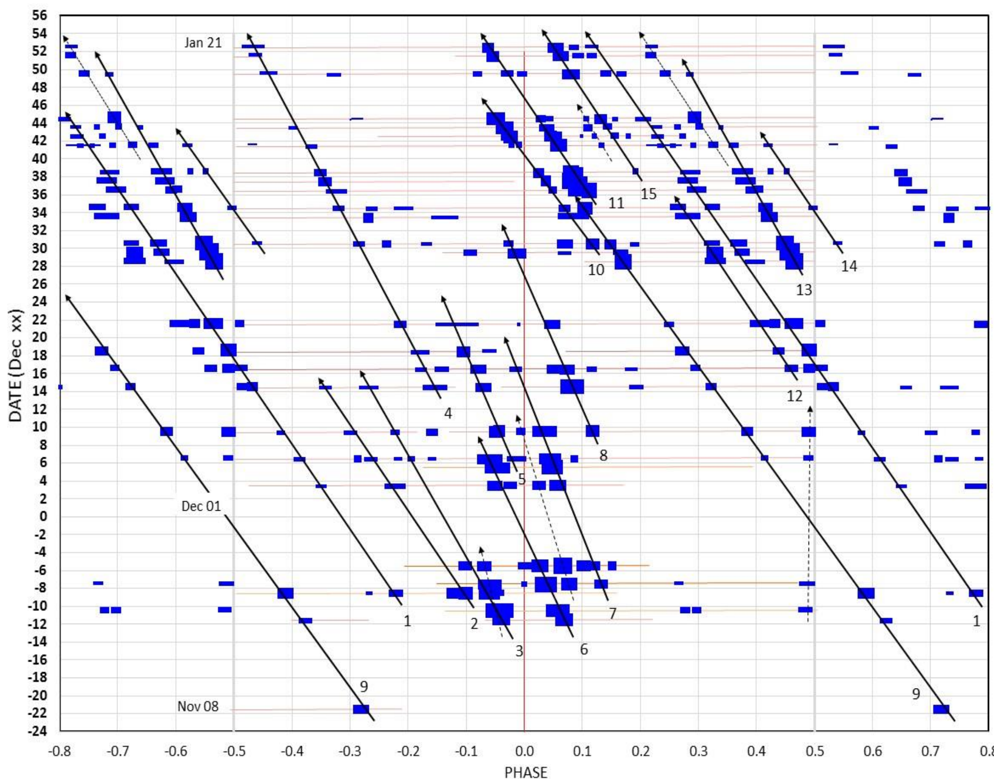

Figure 6. *Waterfall plot for the first 2.5 months of amateur observations. Every light curve "dip" is assigned a phase using an ephemeris for the A-asteroid. For this plot, phase = fractional part of (BJDi – 2457316.6860) / (4.5004 hr / 24 hr/day), where BJD is barycentric JD of the deepest time for dip i. Thickness of symbols is proportional to dip depth; phase length is set by dip length.*

In Fig. 6 we have identified 15 “dip drift lines.” They all drift to the left as date increases upward. The average drift line slope corresponds to a period of 4.493 hrs. The dips in the first half of the waterfall diagram appear to obey the K2 A-period expectation, by occurring at the same phase. Halfway through the 2.5 month of observations we assumed that the dips were caused by dust clouds that originated with the A-asteroid, but then for some inexplicable reason drifted away in an inner orbit with a shorter period.

In Fig. 6 there is also evidence that most dust clouds originate at phase ~ +0.15. The drift lines that originate at some greater phase could be thought of as having “lapped” the A-asteroid, after originating at phase = +0.15 many weeks earlier than our observations began. By this time we were considering that the dust clouds originated with fragments shortly after they broke off the A-asteroid, and that there was a major episode of breaking away some months earlier that caused the dramatic increase in overall dip activity following the *Kepler* K2 and early 2015 professional ground-based observations. In fact, one of the amateur observers (TK) suggested that we could estimate the date of the dramatic rise of activity by projecting drift lines backwards in time to see where they converged. To assist in follow-up of that idea I created a waterfall diagram using the fragment period, 4.493 hr. This is shown in Fig. 7.

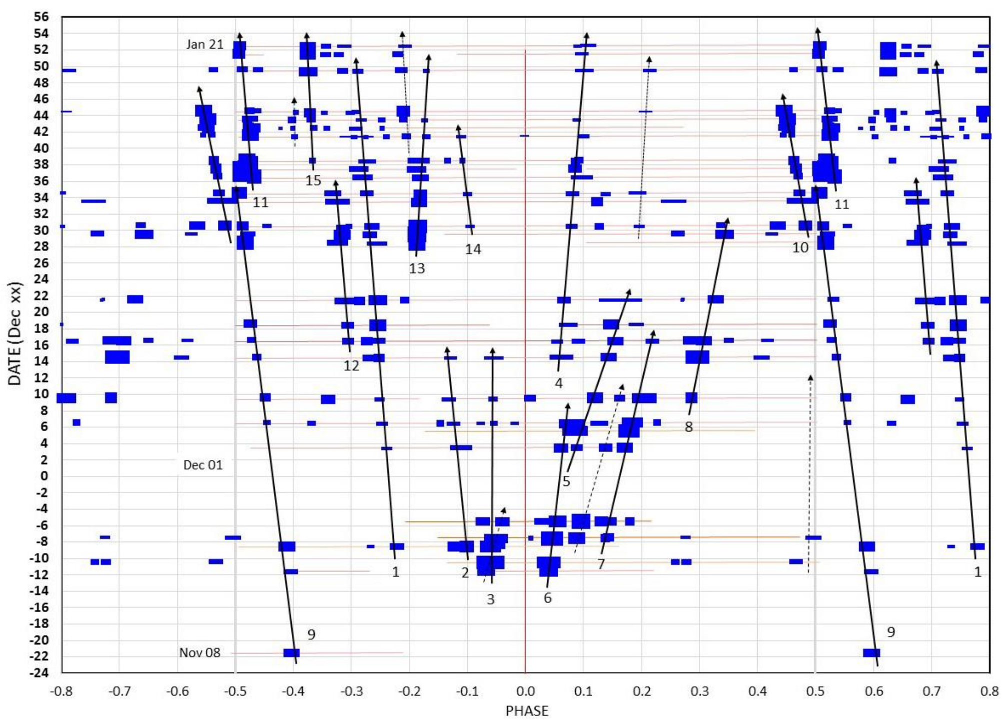

Figure 7. *Waterfall diagram using the dust cloud ephemeris: phase = fractional part of (BJDi – 2457347.9931) / (4.4925 hr / 24 hr/day).*

This waterfall diagram was used to extrapolate drift lines backward in time to a convergence date of 2015 August/September. That is our best estimate of when the A-asteroid began to release fragments as the result of an old, and possible inactive fragment colliding with the A-asteroid. The newly released fragments would have had "fresh surfaces" that were the source for producing dust clouds.

The "drifting dips" was the second contribution by amateur observers to our growing understanding of WD1145. The backward convergence of drift lines to a date in early September, 2015 was a third contribution, but that was tentative and the backward convergence to an origin date was a concept needing confirmation (which we provided in April, 2016, described below).

Crucial Professional Astronomer's Support

During these 2.5 months retired professional astronomer Dr. Saul Rappaport (MIT), who understands white dwarfs well and has extensive modeling experience, encouraged our observing while he worked on developing a theory for interpreting the drifting dips as they relate to the *Kepler* K2 A-period. He suggested that there was an asteroid orbiting so close to the white dwarf star that its "Hill sphere" had shrunk to the size of the asteroid (during an inward orbit migration), and this meant that fragments at the L1 end of the asteroid could simply drift away and reside in orbits slightly smaller than that of the asteroid. The Hill sphere is approximately the surface where the gravitational force of the white dwarf and asteroid, plus centrifugal force, equal zero. Since our observations showed that the dip drifts had a period of 4.493 hours instead of 4.500 hours, a Hill sphere model was used to calculate that the asteroid's L1 location was a distance of ~ 225 km from the asteroid center. This means that the asteroid has a radius of ~ 225 km (corresponding to ~ $1/10^{th}$ the mass of Ceres).

A subtlety of this model is that during the *Kepler* K2 mission the fade activity was limited to dust that was always close to the asteroid, such as by small fragments that didn't produce dust clouds for longer than a few days (during which time they were close to the "mother ship" asteroid); whereas during the 2.5-months of amateur observations there were many fragments breaking away from the asteroid and producing dust clouds that lasted for weeks and months, and these dust clouds dominated the periodicity analysis starting in mid-December. In fact, the amateur observations included this transition from a time of short-lived dust clouds that dominated period determinations near the A-asteroid's 4.500 hour period, to a time of long-lived dust clouds that dominated period determinations near the A-fragment period of 4.493 hours.

The 2.5 months of amateur observations was written-up and submitted for publication to the *Monthly Notices of the Royal Astronomical Society*. The Hill sphere model was described in the paper. It is available as a preprint at the arXiv web site, as article 1602.00740. The authors are S. Rappaport, B. L. Gary, T. Kaye, A. Vanderburg, B. Croll, P. Benni and J. Foote.

After First Article Submission, Observing Continues

I disbanded the observing team after the January, 2016 cut-off date for inclusion of data in the Rappaport et al, 2016 paper, because by then the professionals had begun their planned 2016-season of WD1145 observations. Although I saw little value for amateurs to continue observing, WD1145 is such an irresistible star because of its ever-changing dip patterns and unexpected dramatic changes that I couldn't resist observing it. After adding to the waterfall diagram with February data, I noticed a significant change in the pattern of where dips were occurring. This is shown in Fig. 8.

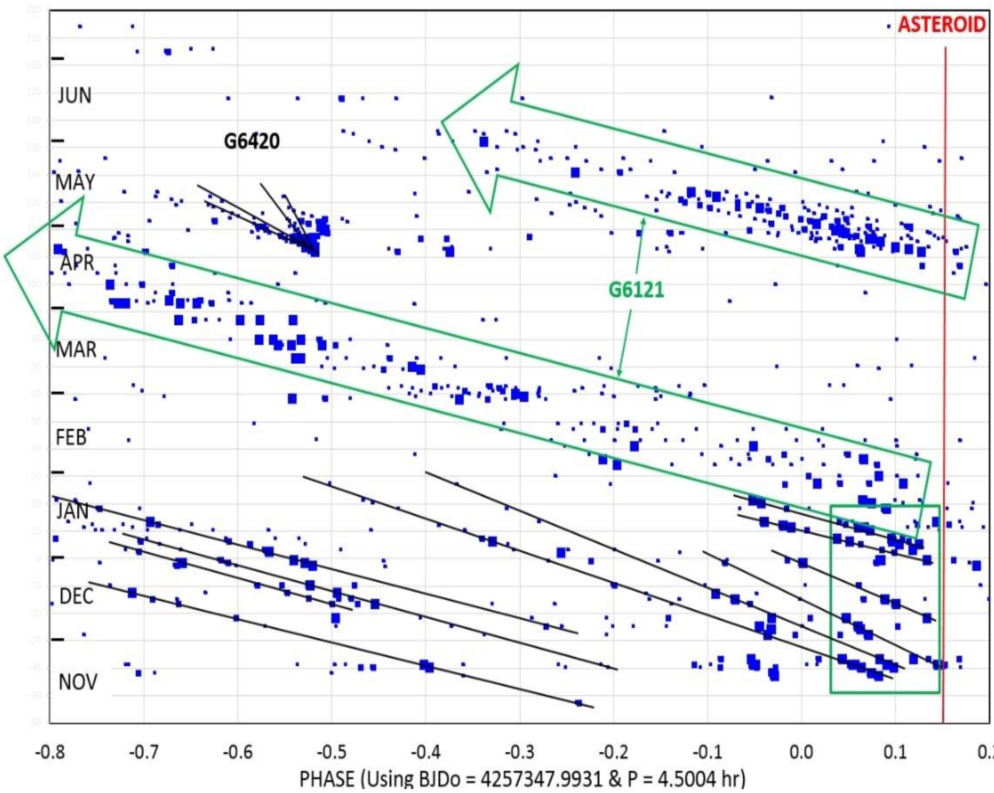

Figure 8. *Waterfall diagram for 8 months of data. Notice that until late January the dips close to zero phase are the most prominent, whereas afterwards there are few dips at this phase region and most dips are confined to a sloped box labeled G6121.*

Something important had occurred in late January, which by coincidence was the cut-off date for inclusion of data in the Rappaport et al (2016) publication. The A-asteroid's creation of fragments ended, and many long-lived fragments appeared with a drift rate corresponding to P ~ 4.4912 hr. This is close to the period of fragments prior to this transition date (4.4926 hrs), but slightly shorter. Hence, this new group of fragments were in a slightly smaller orbit than those that preceded them. This is the fourth contribution by amateur observers to our investigation of WD1145 behavior.

When I noticed this new dip pattern continuing into March, with the overall level of dip activity increasing, I realized that it was time again for me to call on help from advanced amateur observers in order to get better date coverage of whatever WD1145 was going to do next. In April I recruited Y. Ogmen (14", Cyprus), P. Benni (14", Boston), J. Hambsch (20" in Chile, Belgium) and T. Kaye (32", Sierra Vista, AZ). In early April professional astronomer R. Alonso (32" in Canary Islands, Spain) offered to share his observations with my team (Alonso's observations were in support of his observations with the GTC telescope (410", Gran Telescopio Canarias, Canary Islands), which was being used to investigate short-timescale variations of WD1145 dip structure.

April Surprises

On April 21, 2016 I noticed the appearance of dips at a phase region that was far away from the A-asteroid, suggesting that a collision between two fragments had occurred. The drift pattern eventually revealed diverging lines. The pattern was eventually seen to consist of 4 drift lines with a backward convergence date of April 20. This is shown in Fig. 9. There were no dips at this phase region before this date, so this was the confirmation we wanted for the concept that backwards convergence of drift lines could be used to assign a date for the appearance of dips. With a confirmation of the drift line convergence suggestion we gave more credibility to the early September date for the onset of the dramatic rise of overall dip activity (a collision between a fragment and the A-asteroid). This is the fifth contribution by amateur observers to an understanding of WD1145 behavior.

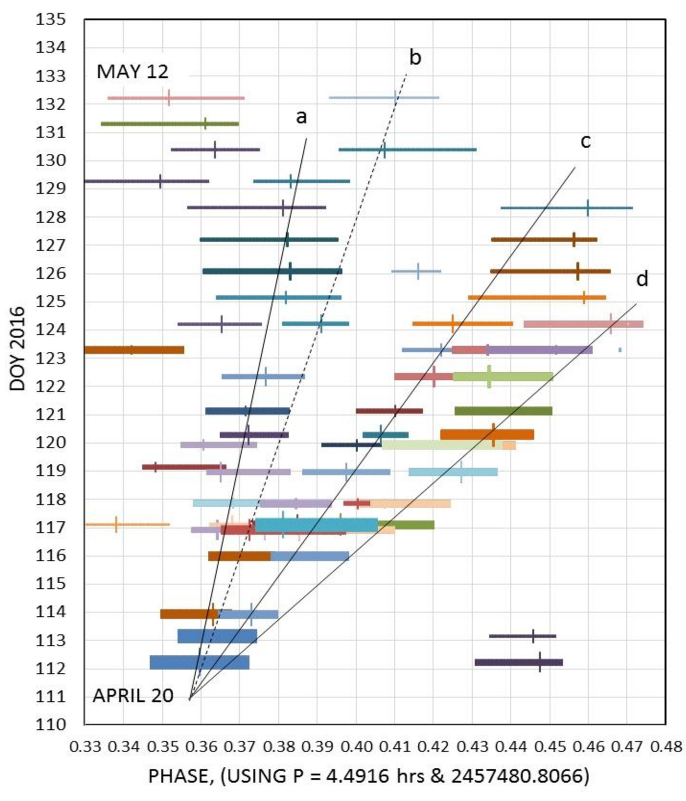

Figure 9. *Portion of a waterfall diagram (using the G6121 fragment ephemeris) showing a pattern of diverging drift lines for 4 dips.*

Also present in the April light curves was the abrupt appearance of a deep but short dip that drifted to higher phases at a fast rate. This is shown in Fig. 10. (The first appearance of this dip is present in the light curves of Fig. 4, 3rd from bottom). The drift rate corresponds P = 4.6064 +/- 0.0002 hours, which is essentially identical to the *Kepler* K2 B-period of 4.6053 +/- 0.0001 hours. This means that all of the Kepler K2 periodicities are probably real, and correspond to asteroids, or their fragments. This is the sixth contribution by amateur observers to an understanding of WD1145.

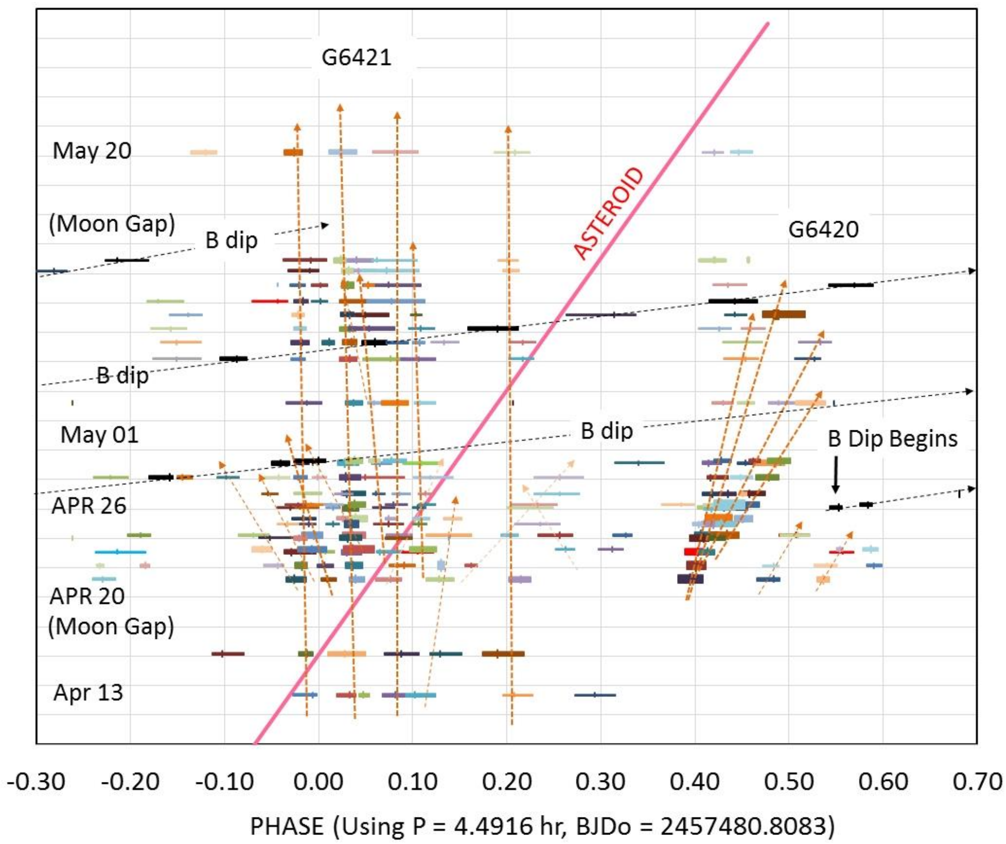

Figure 10. *Water fall diagram for 2016 April/May, showing the abrupt appearance of a dip on April 26 that drifted to higher phases at a high rate. The drift rate corresponds to an orbit period of 4.6064 hrs, which is the same as the* Kepler *K2 B-period.*

Dust Cloud Evolution Described

Since our waterfall diagrams have good coverage, with a median date between observations of ~ 1.5 days, it is possible to identify a specific dip in many light curves. This means that we can measure the depth and width of a specific fragment's dust cloud dip vs. date, for long intervals. Figure 11 is an example of one dip that was easily identified in light curves spanning 4.7 months. The dip "comes alive" on DOY = 32. Several observations before then are "no shows." The product of dip depth times width (times 0.79) yields something we call "equivalent width," which is "area under the curve" using normalized values for flux and width (i.e., width / 4.5 hrs). The abrupt rise of equivalent width, or EW, is most easily explained by a collision between the fragment (which had been dormant before DOY 32) and a smaller fragment (also dormant). EW decreases slowly, then slowly rises, followed by a decline. At DOY 125 it rises abruptly, and is followed by a decline. This pattern is statistically significant. The DOY 125 abrupt rise may be due to another collision with a smaller fragment. But what about the slow rise and decline patterns? These may be due to encounters with a background level of micrometeoroids (i.e., dust left over from previously dense dust clouds). Note that a typical cloud should shear way in a matter of days, due to the different orbital speeds for the inner versus outer edges of the cloud. This means that there must be a quasi-continual production of dust by this fragment. It will be a task for future modelers to identify which of several possible physical mechanisms is responsible for dust production. This matter is something beyond the capability for amateurs to study. But the observational finding that a specific dust cloud undergoes slow variations of activity, for several months, and that dust production activity can abruptly rise, constitute a seventh contribution by amateur observers to an understanding of WD1145 behavior.

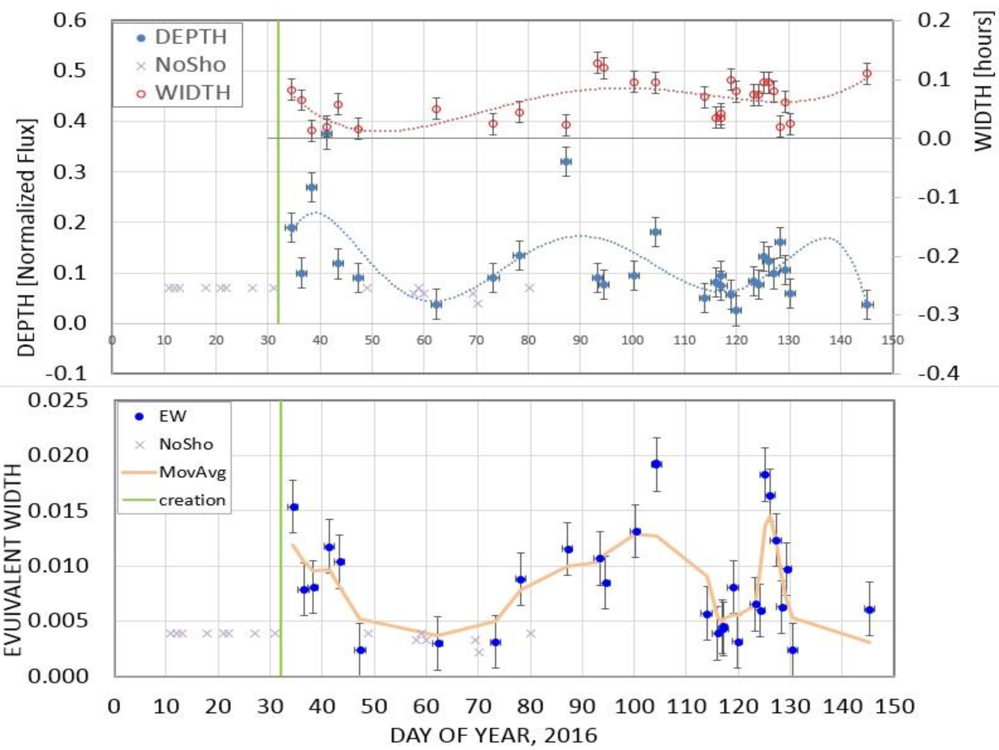

Figure 11. *Upper panel shows a specific dip's width and depth for a 140-day interval. Lower panel shows the dip's activity level ("equivalent width" or "area under the curve") vs. date.*

Overall Dip Activity Levels

Figure 12 is a plot of "overall dip activity level" for WD1145 during the entire 8 months of amateur observations. Our amateur observations begin with activity at a high level, decreases to a low in February, rises to another peak in April, and finally declines to a low level by the end of the observing season in mid-July, 2016.

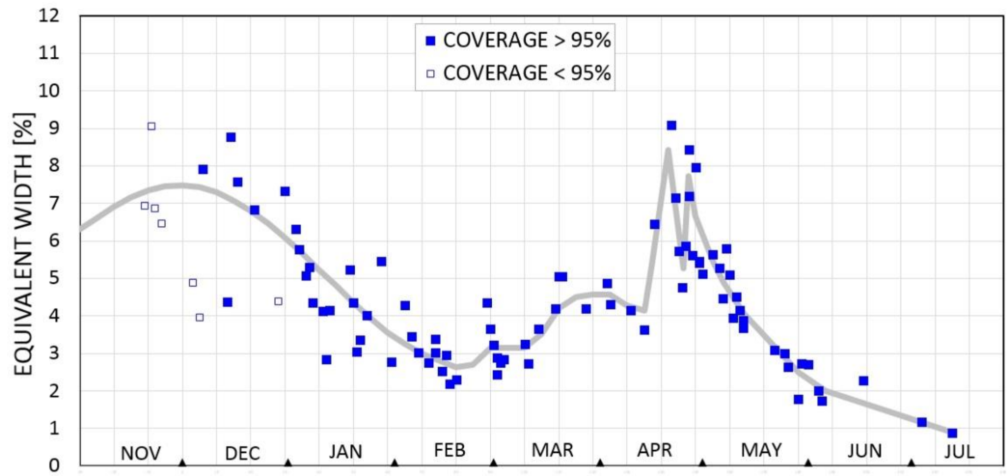

Figure 12. *Overall dip activity level vs. date, using "equivalent width" per orbit as a measure of activity.*

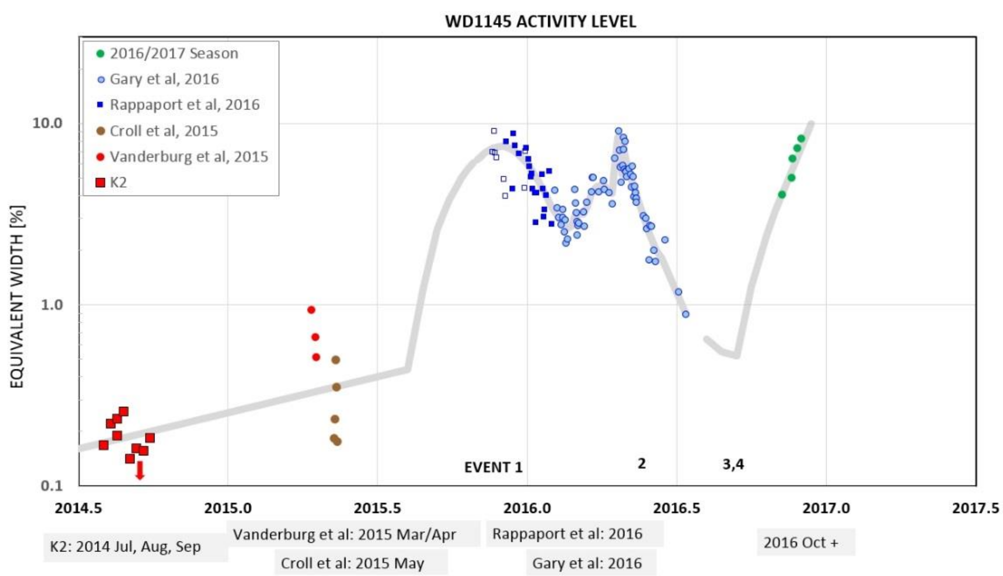

Figure 13. *Overall dip activity level vs. date, with activity plotted using a log scale, and for a date span that starts with* Kepler *K2 observations in 2014 and follow-up ground-based observations by professionals in early 2015. The amateur observing in 2015/2016 reach a peak of ~ 25 x greater activity than earlier, and decline to almost the K2 level. The new observing season reveals a resurgence of activity.*

Figure 13 shows the same data on a log scale for activity level. It also includes measurements by professional astronomers before amateur observing began. It is clear from this plot that the *Kepler* K2, as well as the follow-up professional observations with ground-based telescopes in early 2015, found WD1145 to be at a low level of dip activity. The abrupt rise in activity must have occurred between May 2015, the last date of professional observations, and 2015 Nov 18, when the first amateur observation showed a high level of dip activity. Our backward convergence of drift lines suggest that the abrupt rise in activity occurred during 2015 August/September. We can state that this particular collision of a fragment with its "mother ship" asteroid, produced heightened dip activity that reached the 25-fold level on two occasions, and that activity was > 10-fold greater during most of the 8 months of amateur observations. This result is another contribution by amateur observers to an understanding of WD1145 dip behavior.

The new observing season of 2016/17 is underway, and so far a resurgence of dip activity is apparent. The total amount of lost light during an orbit is now ~8%, similar to the peak for one year earlier.

Dust Cloud Asymmetry

Figure 14 is a plot of dip egress vs. ingress times. When models for dust production are developed it will be important to account for the fact that trailing tails are more common that leading tails. This asymmetry is another contribution of amateur observers to an understanding of WD1145 dip behavior.

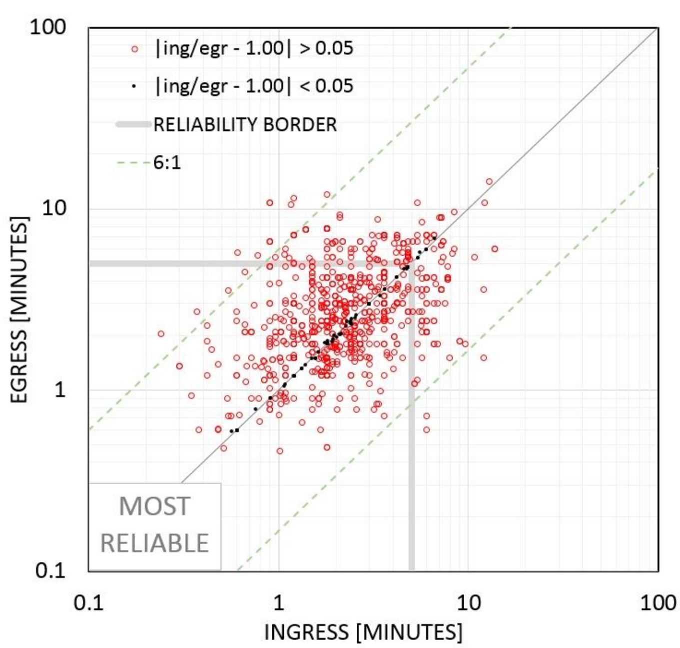

Figure 14. *Dip shape was slightly asymmetric in the sense that trailing tails were more common than leading tails. There are 360 cases of trailing tails versus 262 cases of leading ones. This is statistically significant at the 4-sigma level.*

Infrared Measurements Reveal Excess Requiring a Debris Disk

We now have enough information about WD1145 to begin creating a model for it. The most important fact is that dust clouds transit the white dwarf disk. Because we have a good estimate of the white dwarf mass, and we know the dust cloud period, it is straightforward to calculate that the dust clouds are orbiting at a distance of 0.00541 AU. Since we think the star's size is ~ 1.34 times the Earth, the dust clouds are located 94 times the star's radius. This means that from the perspective of the dust clouds the star has an apparent diameter of 1.2 degree, or a radius of 0.6 degree. If the dust cloud orbit plane were inclined to our line of sight by 0.6 degree the dust clouds would appear to graze one of the poles of the star as viewed from Earth. Such an orbit would be described as having an inclination of 89.4 degrees. For such an inclination only half of a typical dust cloud would then pass in front of the star as it skimmed the pole.

You might wonder why a larger inclination isn't preferred, since it would cause deeper dips for a given dust cloud size. This is because of a reason for preferring <u>smaller</u> inclination values (i.e., < 89.4 degree). There's a "disk of dust debris," left over from dust cloud production, that has to have a large enough projected area to account for an observed excess of radiation at near IR wavelengths (> 2 micron). Figure 15 is a "spectral energy distribution" (SED) plot for WD1145.

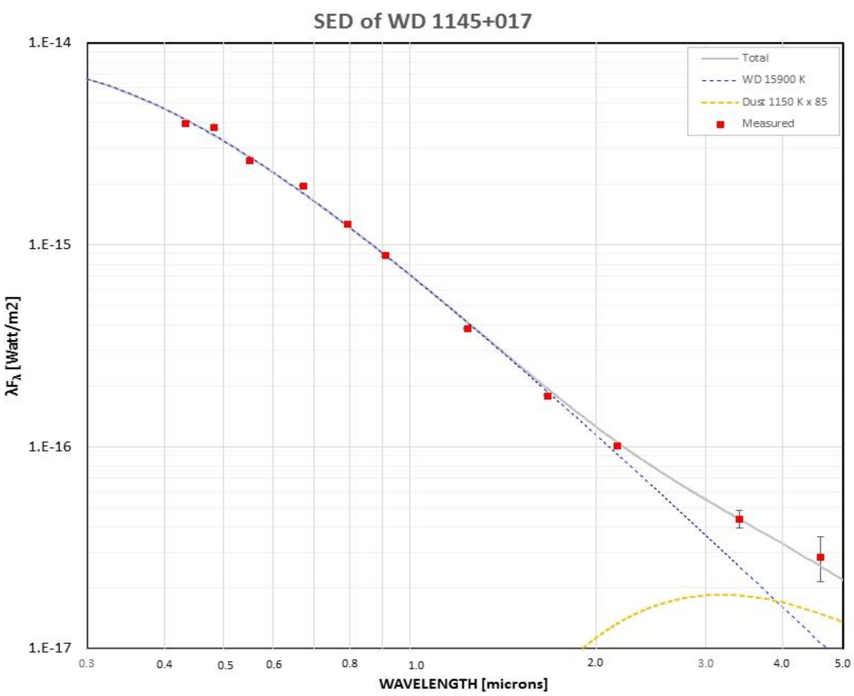

Figure 15. *Spectral Energy Distribution (SED) measurements and model fit, using a blackbody with Teff = 15,900 K for the white dwarf, and a debris disk with average brightness temperature of 1150 K and projected area 85 times greater than the WD1145 disk.*

The “IR excess” seen at 3.4 and 4.6 micron wavelength can be accounted for if the debris disk has a large extent, such as from 94 to 150 times the white dwarf radius (for an inclination of 89.45 degrees). If inclination is reduced to 89.0 degrees, for example, the outer extent of the debris disk could be reduced to ~ 120 times the star’s radius. That’s a radial extent that is approximately defined by the A through F asteroids (based on the *Kepler* K2 A through F measured periodicities). The problem with this lower inclination is that small dust clouds in the A orbit wouldn’t transit the star’s disk; their size would have to exceed the star’s radius in order to produce a transit feature, and then the transit feature couldn’t be short in duration (assuming the cloud was a smooth oval). Since we observe dips as short as ~ 2 minutes long (see Fig. 14), inclination can’t be as small as 89.0 degrees, for example. We have therefore narrowed the range of inclinations that are compatible with observations. This is another contribution by amateur observers to an understanding of WD1145.

Shrinking Hill Sphere Model

Dr. Saul Rappaport suggested a model to explain how fragments leave the asteroid and enter orbits around the white dwarf that are slightly smaller than the asteroid’s orbit. The model was described in the paper by Rappaport et al (2016). It invokes something called the “Hill sphere.” The Hill sphere of an asteroid is usually described as the region within which smaller objects can remain in orbit. Any object outside the Hill sphere is free to simply drift away, and in this case enter an orbit around the white dwarf. Along the line joining the asteroid and the white dwarf the location of the Hill sphere surface intersecting that line is easily calculated as the place where the sum of three forces add to zero (two gravity field forces and the “centrifugal force”).

When the asteroid is far away from the white dwarf the “Hill sphere” is indeed a sphere, and it is large. If the asteroid’s orbit of the white dwarf shrinks slowly, over many millions of years for example, the Hill sphere will shrink also, and eventually take on the shape of a football with one end pointed at the white dwarf, as depicted in Fig. 16 by a hatched region. It is possible that the Hill sphere will shrink so much that part of the asteroid’s surface protrudes beyond it, also shown in Fig. 16. In this case any loose objects that had been resting on the asteroid surface that end up outside the Hill sphere will simply drift away and enter an orbit of the white dwarf. Within our solar system essentially all asteroids are oblong (only Ceres, the largest asteroid, is approximately spherical.) If asteroids around WD1145 are similarly oblong, we can assume that their longest axis will be pointed at the white dwarf (a minimum energy orientation due to the strong gradients of the white dwarf’s gravity field).

The L1 end of the asteroid will be the hottest place on the asteroid because it is heated by the white dwarf, whereas the sides, and the L2 end, will be cooler because they are shaded. An asteroid at the A-orbit distance from the white dwarf should reach temperatures of ~ 1700 K at L1, which will melt most materials. The L1 end will either produce melt that drifts away, or cracks will form and fragments will drift away. Since that material, which I’ll refer to as a fragment, is close to the white dwarf when it becomes free of the asteroid, yet has the orbital velocity of the asteroid, it will drift ahead of the asteroid (an upward motion in Fig. 16). The dotted trace in Fig. 16 shows a calculated orbit (by Rappaport) for such a fragment. The fragment trajectory has a curved path in this rotating coordinate system due to the gravitational force of the asteroid slowing the fragment's departure. When the fragment escapes the asteroid's gravitational influence it will be in an orbit around the white dwarf that is smaller than the asteroid's orbit. The average distance between the two orbits will be 4 times the Hill radius (which is ½ the asteroid's long diameter).

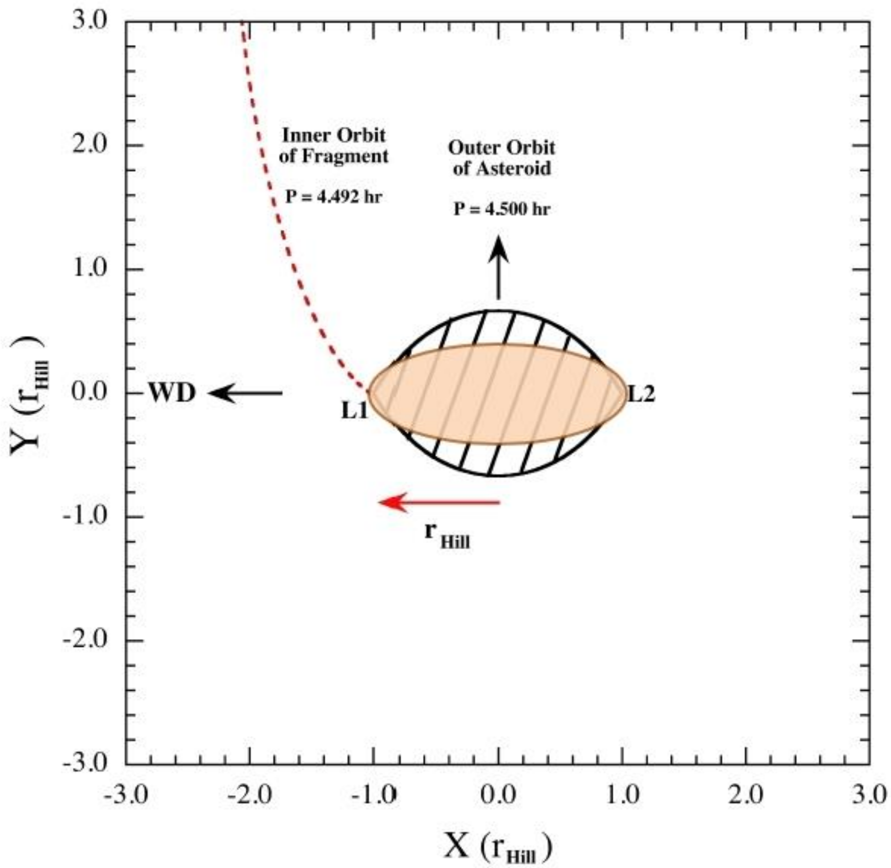

Figure 16. *Shape of Hill sphere (hatched region, shaped like football) centered on an oblong asteroid (brown oval). The coordinate system is rotating in a way that keeps the asteroid at the center of the diagram. In an inertial reference frame the asteroid would be orbiting in an upward direction. [This figure, minus the asteroid oval, are taken from Rappaport et al, 2016.]*

When the fragment produces dust clouds that produce transits of the white dwarf as viewed from Earth we are able to measure the orbit period of the fragment. We know the orbit period of the A-asteroid, and we can infer the orbit period of the dust clouds from the drift rates of the clouds with respect to an A-asteroid ephemeris. This allows us to determine a size for the Hill radius, which we equate with half the longest diameter of the asteroid. Figure 17 shows the relationship between drift rate and asteroid diameter.

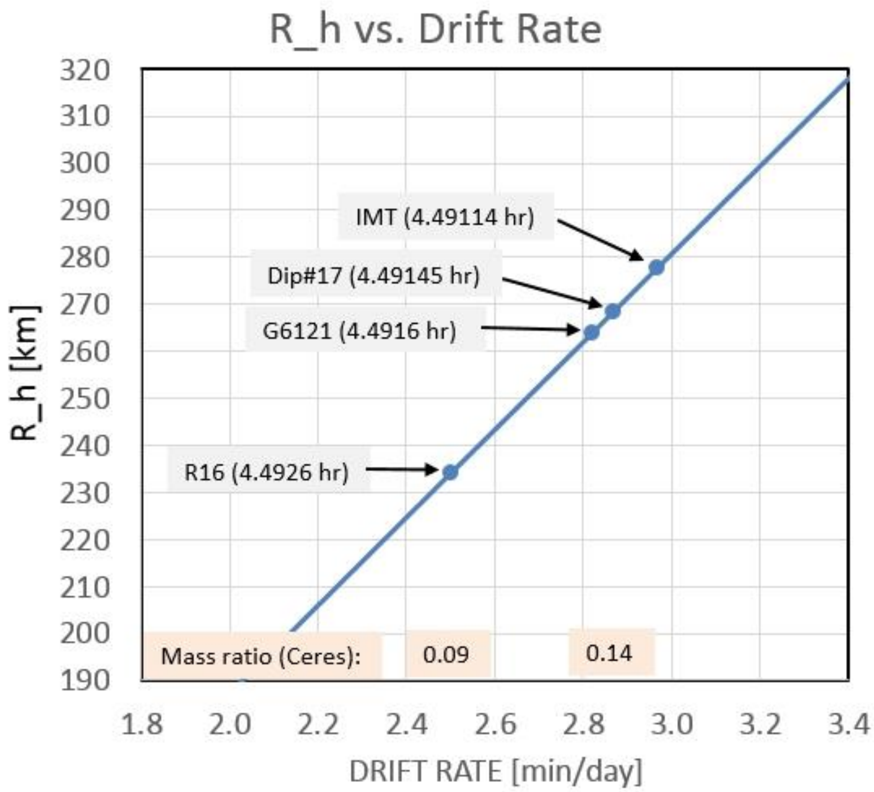

Figure 17. *Asteroid diameter vs. dust cloud drift rate, for the A-asteroid. Four well-determined drift rates form a consensus of 2.8 minutes/day, which could be produced by a Hill radius of 65 meters. Four times this radius yields a diameter of 260 meters in the long direction.*

Others have calculated that the volume of the football-shaped Hill sphere is ~ 52% of the volume of a spherical Hill sphere with the same Hill radius (for these conditions). If the asteroid is soft enough to "fill" the football-shaped Hill sphere then we can derive a mass for the asteroid by assuming a density, such as 3.0 [gm/cm^3]. Two mass values are given in Fig. 17 at their corresponding drift rates. The asteroid has an approximate mass of 1/10 the mass of our asteroid Ceres.

Migrating Asteroids as the Source for Debris Disk

In the previous section it was assumed that asteroids of a white dwarf will migrate to smaller orbits over long timescales, such as many millions of years. The process that produces this migration has not been determined, but it is obvious that such a migration does occur (note: the A-asteroid is at 0.0054 A.U., and during the evolution from main sequence star to a white dwarf the star must have swelled to ~ 0.7 A.U., at which time the asteroids and planets that existed during the main branch phase, and which survived the red giant swollen phase, were at distances greater than ~ 1.5 A.U.). Several asteroids, planets and comets can be migrating inward simultaneously. Each has a unique starting density.

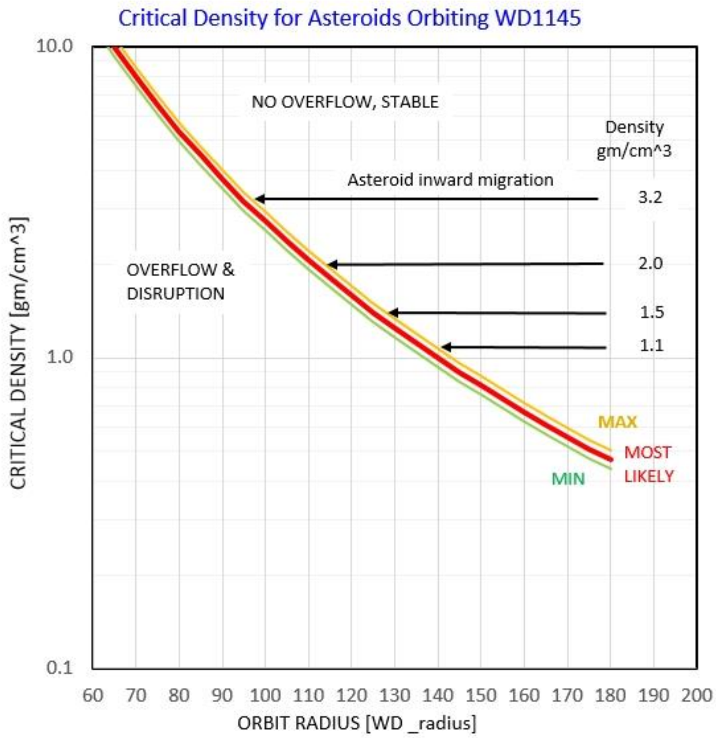

Figure 18. *Orbit shrinkage tracks can't move past the curved traces because that's where the Hill sphere radius shrinks to the size of the longest axis of the asteroid having the asteroid's adopted density. The three colored traces correspond to uncertainties associated with our imperfect knowledge of the white dwarf's size, mass and the shape of the asteroid.*

In Fig. 18 the asteroid with a density of 3.2 [gm/cm^3] migrates inward until it is ~ 94 times the white dwarf's radius, at which time the Hill sphere has shrunk to the size of the asteroid's longest dimension. Any additional inward migration will cause additional loss of material from the asteroid, and as long as it has the same density it won't be able to migrate farther inward. If the asteroid has a high density core, such as being the remnant of a planet originally, it will move up in the diagram and be allowed to migrate inward; it will thus "slide" along the curved lines until it is completely eroded away. During this process dust clouds will have been produced, and sheared into a ring structure, at all radii where erosion was occurring.

Asteroids that begin with a lower density will commence their erosion starting at greater distances from the white dwarf. In this manner it may be possible to create spread-out dust rings spanning a range of distances. In Fig. 18 this range is shown extending from 94 to 140 times the white dwarf's radius. Since more asteroids are expected to exist with densities in the 2.0 to 3.2 [gm/cm^3] range we can expect the ring system to have a greater number density of particles in the distance region 94 to 110 times the white dwarf radius. This is consistent with the measured IR excess, described above.

Assembling an Overall Model

My first attempt at constructing a diagram for a model used inclination = 89.45 degrees, and is shown as Fig. 19. The A-asteroid orbit, and the A-fragment orbit (which are so close to each other that they are indistinguishable in such a diagram) are shown as a thick brown line passing in front of the star disk crossing the upper polar region (labeled 94 on the right side). Along the orbit path is a black dot, the size of the A-asteroid. Also on the orbit path are three oval dust clouds. Imagine that the A-asteroid and the dust clouds are moving to the right. The largest oval is shown with a longer trailing tail than leading tail (which our data shows is more common). The outer bands (tan in color) represent the debris disk, extending from 94 to 150 times the star's radius.

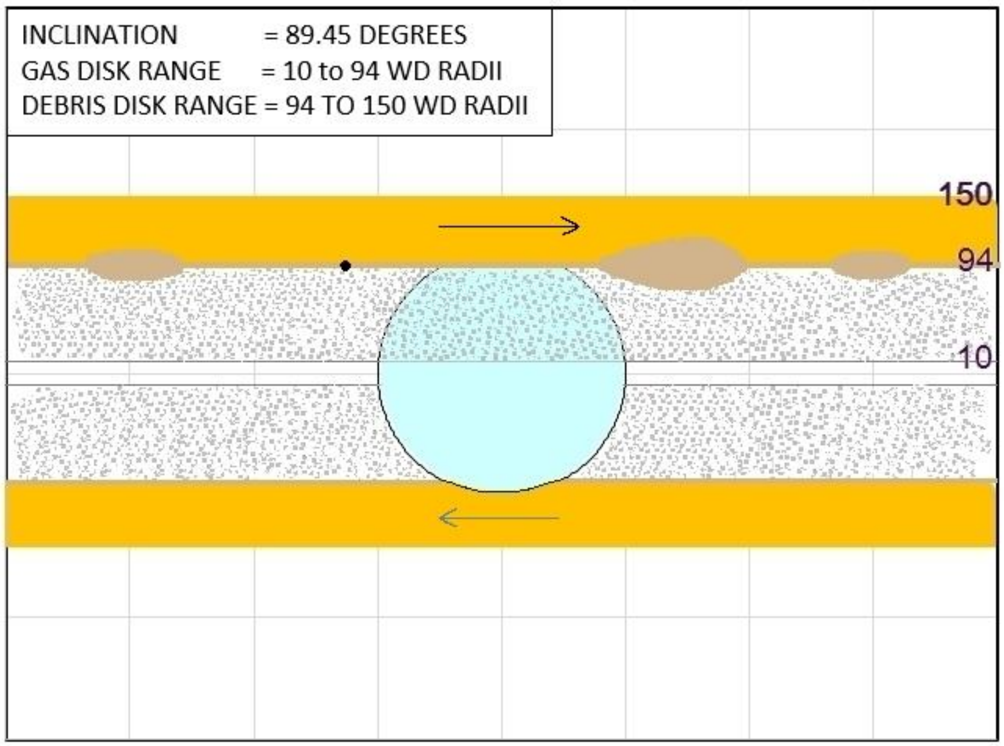

Figure 19. *An artistic representation of how WD1145 would look from the Earth's perspective. The black dot represents the A-asteroid, moving to the right and about to produce a transit of 0.08% (too small for detection). The three brown ovals are dust clouds produced by fragments that have broken off the A-asteroid. Our light curves show fades (also called "dips") produced by dust clouds that expand and cover part of the WD disk. The middle dust cloud in this depiction is large enough to have produced a 4% dip (which is detectable using amateur telescopes). The dark tan bands are a debris disk, consisting of spread out dust leftover from dust clouds. The debris disk is opaque at the inner regions, and may become transparent due to low dust density in the outer regions. Small dust particles may be the source for atoms that sublimate away and never re-condense, which eventually form a disk of metal atoms (such as iron, calcium, aluminum, etc.) in an inner gas disk (represented by dotted regions in the*

diagram). The metal atoms absorb light at only specific wavelengths, so most of the WD's light passes through the gas disk; it is therefore essentially transparent. We believe that both disks have as their source dust from fragments that have broken off the A-asteroid (and 5 others, in slightly larger orbits in the debris disk). The numbers on the right edge show radial distance of edges of the ring system: the inner gas ring begins at 10 x WD radius, the A-asteroid and associated fragments are at 94 x WD radius, the inner edge of the debris disk is also at 94 x WD radius, and the outer edge of debris disk is at ~ 150 x WD radius.

Note in Fig. 19 that closer to the star than the A-orbit is a dotted region referred to as a "gas disk." This is a speculation by others (Rappaport, personal communication; Redfield et al 2016) meant to explain why the spectrum of WD1145 has a component of absorption that is inexplicably broad. This very broad absorption spectrum is shown in Fig. 20 using observations by Siyi Xu.

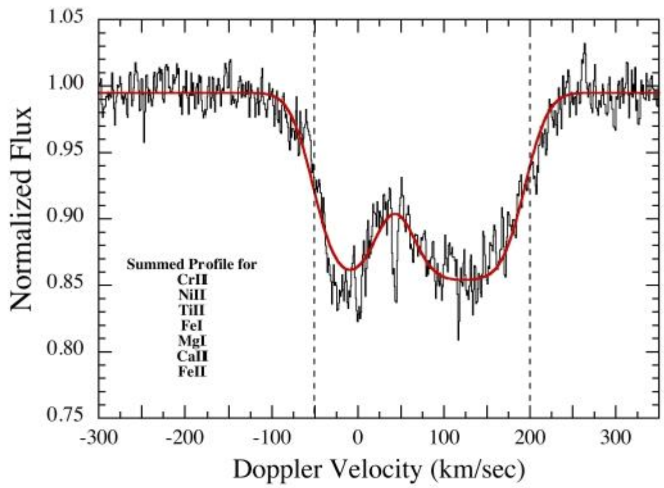

Figure 20. *Xu et al (2016) average spectral shape of the "broad" category of absorption lines.*

The broad absorption spectrum in Fig. 20 requires atoms (not dust) to be present along some portions of the line-of-sight to the star disk that are traveling at high rate of speed away from the Earth (~ 200 km/s) and other portions of the line-of-sight to the disk that are traveling toward the Earth (~ 50 km/s). This range of velocities, ~ 250 km/s, could not be associated with the white dwarf atmosphere, which has a rotation speed at one limb (on the equator) that is probably < 1 km/s (i.e., corresponding to star rotation P > 15 hr). The "photospheric" absorption lines are therefore much narrower than the easily recognized "circumstellar" component of broadened lines. Can we get such broad lines from circumstellar motion? Yes, if the gas of atoms (some ionized, some neutral) are in orbits as small as 10 x the star's radius it would be traveling in an orbit at ~ 980 km/s. A tube of gas at this distance would be seen crossing the disk, from Earth's perspective, that has a component of ~ 90 km/s at one limb and a receding component of ~ 90 km/s at the other limb. Hence, a broadening of ~180 km/s would be seen for gas orbiting at 10 radii. If the gas was orbiting with an eccentricity of 0.10, for example, the entire absorption pattern could be shifted by ~ 100 km/s. As proposed by Redfield et al (2016), an eccentric gas disk extending from 10 to ~60 radii could account for the broad absorption features observed in the WD1145 spectrum.

Fig. 19 shows the gas disk extending out to the A-orbit, since the observations cannot rule this out and such a model is simpler. It corresponds to atoms being produced from dust clouds, and being in orbits that, due to some mechanism, spiral inward to fill in the gas disk. The lack of gas closer than 10 radii may be due to a magnetosphere that captures the ionized atoms at this distance and quickly forces them to follow magnetic field lines to the surface (Redfield, et al, 2016).

What could cause atoms to be produced from dust clouds, and then spiral inward? The temperature of crater bottoms on fragments at the A-orbit distance can be as hot as 1900 K (Keihm, private communication, 2016). This is hot enough to melt most metals, causing surface material to sublimate. Some of the atoms could re-condense if their number density is great enough, which it might be near the fragment surface (before the atoms have traveled far from the fragment). Re-condensed dust particles is one theory for what the dust clouds are made of (Vanderburg et al, 2016). Atoms that don't re-condense to dust particles will be present as a gas, and will absorb light at wavelengths specific to that atomic element. Even re-condensed particles could be a source for dislodged atoms if the dust particles are subjected to a micrometeoroid bombardment. This is also true for grains of dust that result from fragment/fragment collisions, since a distribution of particle sizes is likely to result from such collisions.

But what could produce an inward spiral of atoms? This will be a problem for modelers to confront, but I would like to suggest that any atom that spends part of its time ionized may encounter a "headwind" of force related to the white dwarf's magnetosphere. The ionized particle will lose orbital angular momentum, and will therefore move to an ever-smaller orbit.

Are All White Dwarfs Like WD1145?

It is apparent that conditions around WD1145 are so unique that new physical models will be needed to explain what we have already observed. Because WD1145 is so unusual it will be the subject of many future observations, with ever-better observing capabilities. But WD1145 is unusual mostly because of its favorable inclination. If all white dwarfs were like WD1145, and if all those with inclinations within the range 89.3 to 89.7 degrees, for example, would resemble WD1145, then statistically we would have to observe ~ 250 white dwarfs to find one that was oriented favorably. If, further, about 1/3 of white dwarfs are doing what WD1145 is doing, then we would have to observe ~ 750 white dwarfs to statistically expect to find one like WD1145. It is estimated that 25% to 50% of white dwarfs have metal absorption lines, so this 33% assumption is reasonable. If we combine the 33% statistic with the 89.3 to 89.7 degree inclination requirement, then we can explain why the Kepler K2 mission, that analyzed ~ 860 white dwarfs, found only one that behaved like WD1145. Therefore, we must consider that WD1145 is like 1/3 of white dwarfs, but is simply one of those very few that can be observed in a way that reveals the processes involved by white dwarfs in general as they cannibalize their remnant solar system. If all white dwarfs cannibalize, and the fraction of time this occurs is ~ 1/3, then WD1145 may in fact be showing us what all white dwarfs do during part of their lifetimes. WD1145 may therefore be a "Rosetta Stone" for deciphering how white dwarf systems behave.

The observing season for WD1145 ended in July. I'm the lead author on a paper submitted to MNRAS in which we describe most of the results in this write-up. This paper is in the public domain as an arXiv posting; the complete co-author list and arXiv link are given in the References section, below. So far no other observing group has posted their paper at the arXiv web site, but we expect that at least two professional astronomer groups are still preparing observational papers. We have reported on 158 observing sessions during an 8-month interval, which includes model fits to 870 dips. I doubt that the professional projects will have this much observational data to report, so they will be less able to see the patterns that we have seen, and to describe what we have in our two amateur-based observational papers. If I am right, then we will have illustrated the value of amateur observations for a project such as this, where changes that occur on a timescale of a couple days need to be monitored as often as only amateurs are capable of in order to unravel the puzzle presented by the target star.

The past 9 months have been exhausting, and I'm glad WD1145 is currently too close to the sun for observing until next November. I'll be ready, then, to see what new surprises this fickle star has in store for us Earthly observers.

Summary

In this summary I am going to emphasize what specifically our 8 months of amateur observations have contributed to an understanding of WD1145, which probably can be generalized to all white dwarf systems. I'll insert numbers in red brackets after a major contribution has been described.

Before our observations it was assumed that WD1145 had 6 asteroids that produced dust clouds, and the A-asteroid was the most active. After the 3rd week of our observations, in late November, 2015, our data showed that the dust clouds associated with the A-asteroid were coming from fragments in orbits slightly smaller than the A-asteroid orbit, and that the A-asteroid was producing an insignificant amount of dust **[1]**. A mechanism was needed to account for essentially all of the dust clouds coming from fragments in slightly smaller orbits, and Dr. Saul Rappaport, who was the only professional astronomer on our team and who did modeling, suggested that Hill sphere shrinkage as asteroids migrate to ever smaller orbits could explain this observational finding **[2]**. If the asteroid end facing the white dwarf extended outside the Hill sphere any loose material, or fragments that broke off, could simply drift away and enter an orbit of the white dwarf, and that orbit would be smaller than the asteroid's orbit.

Until mid-December, 2015, dust clouds were most active close to their breakaway from the asteroid, so this allowed us to confirm that the A-asteroid was in an orbit that matched the *Kepler* K2 orbit (4.500 hours). After mid-December the dust cloud activity was longer-lived, and the only periodicity in light curve data was the A-fragment period (4.493 hours). In other words, the waterfall plot showed only dust clouds drifting with respect to the A-asteroid period, and these dust clouds lasted for over a month. This required that dust production by the fragments was continuous, not episodic **[3]**, since a single episode of dust production would last only a few days before differences in orbit periods for various parts of the dust cloud would spread the cloud around the orbit in a way that would reduce depth to an unobservable level, and at the same time greatly increase duration of the fade feature. Instead, the fade depth remained relatively constant, as did the duration, and this required constant dust production.

We submitted a paper to MNRAS based on observations up to January 21, 2016. Although I disbanded the observing team I continued to observe, and by late February I noticed three unusual things: 1) the overall activity level of fading events had declined significantly (see Fig. 12), 2) there were no more fragment dust clouds (i.e., drifting dip features) originating from the phase location of the A-asteroid (see Fig. 8), and 3) there was a large group of fragment dust clouds drifting together with a period of 4.4916 hours (see Fig. 8). I reconstituted some of the earlier observing team in order to better understand these changes.

On April 21 we discovered the sudden appearance of a group of dust clouds with waterfall drift lines that on subsequent days revealed that the fragments producing the dust clouds were moving away from each other with significant speeds, and the diverging pattern of drift lines projected backwards to a single phase corresponding to an apparent origin date of April 20. The phase for the collision was far from the A-asteroid location, so the simplest explanation was that two fragments collided on April 20, and produced 4 fragments that within a few days were active in producing dust clouds. This confirmed a hypothesis stated in our first paper that backward projection of drift lines to a convergence date could be used to determine when a collision occurred **[4]**. With that demonstration we were able to interpret the pattern of diverging drift lines shown by our waterfall plots for November, 2015 through January, 2016 (see Fig. 7) in terms of a collision in August or September, 2015 (between a fragment and the A-asteroid) that led to the dramatic 25-fold increase in activity that was first seen in our November, 2015 observations (shown in Fig. 13) **[5]**.

On April 26 our team observed a dip that abruptly appeared showing in subsequent days to have a very high drift rate corresponding to a period of 4.6064 hours. This is the same period as measured by *Kepler* K2 that was named the B-period. This implies that all 6 of the *Kepler* K2 periods, A through F, are valid, and correspond to real asteroids [6].

Observations after late April showed a steady decline in overall activity level until the last observation in mid-July, 2016. The last observation was at an activity level close to what had been observed by *Kepler* K2 in mid-2104 and by sporadic, brief observing sessions by professionals in early 2015. The amateur observations, that reached activity levels up to 25 times greater the earlier *Kepler* and professional levels, provide an initial estimate for how long heightened activity can last when a fragment collides with an asteroid, and that about one year [7]. It remains for future observations to show how often these yearly episodes of heightened activity occur for WD1145.

The modeling of WD1145 is constrained from many directions. The tightest parameter solution is inclination. It has to exceed 89.3 degrees in order to account for the many brief fade events, but in order to account for the IR excess measurements produced by a debris disk (assuming it's co-planar with the A-asteroid) inclination must be smaller than ~ 89.7 degrees. The A-asteroid must have a longest diameter of ~ 260 meters, in order to account for the fragment dust cloud drift rates with respect to the A-asteroid orbit period. This size is compatible with an A-asteroid density of ~ 3.2 [gm/cm^3]. The appearance of a B-dip implies that the B-asteroid has a lower density, and assuming the *Kepler* K2 periodicities extend to periods of 4.9 hours the F-asteroid would have a density as low as 2.0 [gm/cm^3]. The range of periods corresponding to A- through F-asteroids implies that if they are all producing dust clouds a ring system extends from 94.6 times the white dwarf's radius to at least 110 radii. The IR excess measurements could be more easily explained if the outer edge of the rings system is farther out, such as 140 or 150 radii.

Inside the dust ring system is a gas disk, composed of atoms, some ionized and others neutral. The atoms must come from sublimation of dust particles close to the inner edge of the dust ring (i.e., A-fragment orbits, at 94.6 white dwarf radii). The gas disk must extend to 8 or 10 white dwarf radii in order to account for the component of broad spectral absorption lines observed in the visible spectrum by several observers. The outer extent of the gas disk is uncertain, but it may coincide with the A-fragment dust clouds.

Collisions determine activity level on both short and long timescales. For the case we documented, the collision of a fragment with the A-asteroid (early September, 2015) initiated a yearlong pattern of heightened activity consisting of two phases. First, the asteroid released fragments at intervals of a few days that were most active in producing dust during the first week after release (allowing detection of the A-asteroid's period). Second, after 3 or 4 months of sporadic releases of fragments (i.e., mid-December) a large number of fragments were released that remained active for half a year. This major release event marked the end of A-asteroid production of fragments. There are so many fragments in orbit (probably from past episodes of heightened activity) that fragment/fragment collisions are common. When one of the fragments is much smaller than the other we observe either an abrupt turn-on of dust production or an abrupt rise in dust production superimposed upon a pre-existing continuous rate of dust production.

Most of the major contributions of the amateur observations could not have been made with occasional observations, such as many days apart. Only amateurs can afford to observe every clear night, all night, and we achieved a median interval between observations of about 1.5 days. Our observations are an excellent demonstration of pro/am collaboration. Big and expensive telescopes are needed for specific objectives (such as spectroscopic observations, or multi-wavelength observations of depth dependence on wavelength), while small telescopes, operated by amateurs, document dip behavior on daily timescales.

A professional astronomer (someone who is deliberate in accepting new ideas for explaining observations) would say that this write-up does an excellent job of over-interpretation of observations! Yes, but if only half of what I'm suggesting is correct then WD1145 would still be an amazing star system, and important for understanding what happens to most stars after they evolve to the white dwarf state. And I must admit, this project, and my over-interpretation of it, was fun!

A Closing Thought

I like to think that our sun will someday resemble WD1145 after it becomes a white dwarf in ~ 5 billion years. If the universe lasts 100 billion years or more, then we could say that WD1145 is showing us what our solar system will be like for most of its existence.

When I'm in a poetic mood, between long hours of observing WD1145 and processing images to produce light curves, I wonder if someday in the distant future some atoms that are now in my body will be part of a dust cloud that obscures our diminutive sun from the telescopic observations of some future alien, possibly an amateur observer, who is observing our solar system! How fitting that would be!

"…all the noonday brightness of human genius are destined to extinction in the vast death of the solar system, and … the whole temple of man's achievement must inevitably be buried beneath the debris of a universe in ruins." Bertrand Russell, 1903, *Independent Review*, (also reprinted in *Mysticism and Logic* as Chapter 3, W. W. Norton and Company, New York, 1929)

Acknowledgements

Although I wrote this entire document, and all figures (except two) are mine, I owe a great debt of gratitude for guidance to Dr. Saul Rappaport, who never tired of answering e-mail questions about things that were new to me (e.g., Hill sphere) yet essential to understanding the WD1145 system. I of course want to acknowledge the observational contribution of all observers on the teams I recruited; this acknowledgement is described fully in the *MNRAS* publication Gary et al (2016).

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http://www.brucegary.net/zombie3/ (web page for 2017 observations, with extensive, detailed information about this amateur project)

http://www.brucegary.net/zombie4/ (web page for 2016/17 observing season.)

Addendum: After writing the paper that has been accepted for publication by MNRAS (Gary et al, 2016), in collaboration with Dr. Saul Rappaport, I was frustrated (as usual) with constraints imposed for scientific journal writing that I needed to write a version that was easier to understand (this PDF). Its purpose is to inform colleagues who want a quick and easy read of what the amateur observations have revealed without wading through the jargon-filled arXiv paper. My goal is also to include results post-dating the arXiv paper. After the 8-months of observing and processing of everyone's data, and the writing of a paper for submission to a scientific journal, I finally had free time for analysis and modeling that had eluded me before (I was envious of Saul, who wasn't bogged down by observing work). My plan is to update the web page where observations for the new observing season of 2016/17 are found, and to update this document at intervals, until I tire of the project.