# Computer Animation of Extensive Air Showers Interacting with the Milagro Water Cherenkov Detector

Miguel F. Morales

*Department of Physics, University of California, Santa Cruz, CA 95064, USA*

We employ advanced computer animation to visualize the interaction of Extensive Air Showers (EAS) with the Milagro water reservoir. The animations help conceptualize the evolution of the EAS particle front as it hits a large volume of water and converts to a front of Cherenkov photons. Expected effects such as refraction and curvature are easily seen, as well as a number of novel behaviors. A simple model that explains the observed dynamics of the shower front is presented.

## Introduction

In recent years advanced computer visualization tools have become available to the scientific community. Visualization offers a very powerful way of analyzing and understanding scientific data, particularly when examining new or poorly understood situations. To create useful fits and histograms for automated data analysis, one needs a conceptual understanding of the experiment. It is in developing this conceptual understanding and in formulating models that data visualization can be an indispensable research tool. The models derived from the visualization can then be used for traditional data analysis.

The Milagro experiment is a case in point. Milagro is a water Cherenkov gamma ray telescope, and is the first air shower telescope of its kind (1). The particle front of an EAS enters the Milagro reservoir at relativistic speeds and is quickly absorbed by the water, being replaced by a front of Cherenkov photons. In principle it is a very simple design, but there are a number of subtleties involved. For example, the Cherenkov photons are not emitted parallel to the incoming EAS particles and are travelling at the speed of light in water, significantly slower than the particles in the EAS. In order to examine how these subtleties affect the formation of the Cherenkov light front, I developed a method for creating 3D animations of the EAS as it interacts with the Milagro pond. These animations showed a number of interesting and novel behaviors we had not antici-

pated, and has led to a new model of the EAS-pond interaction.

This paper will focus on explaining the model of the EAS-pond interaction that was developed using insights gained from the computer animations. Unfortunately, the computer animations themselves are nearly impossible to present in printed form. All of the animations are available on the web, and there is a separate web site for the animated figures referred to in this paper. Animations viewable on the web will referred to as Web Figures (e.g. Web Figure 2), and can be seen at http://scipp.ucsc.edu/milagro/Animations/Snowbird99.html. This site also includes a full description of how the animations were produced.

## Bowl-Ring Model

Computer animation techniques were used to create a set of movies showing the interaction of an EAS and the Milagro Pond. After studying the animations in some depth, it became apparent that there were several unexpected phenomenon. This is most dramatically seen in Figure 1a, where an EAS initiated by a 2 TeV gamma ray from zenith is interacting with the Milagro pond. Since we are viewing the pond and shower from the side, we would expect the classic ring Cherenkov light ring to appear as a thin band. However,in addition to the Cherenkov ring, a bowl of Cherenkov light can easily be seen. In Figure 1b the perspective is changed slightly to clearly show a thin bowl of Cherenkov light with a single bright band circling the bowl.

The bowl and ring structure is coincident with the core of the EAS shower, and can be explained by multiple scattering. The particles of the EAS are moving relativistically

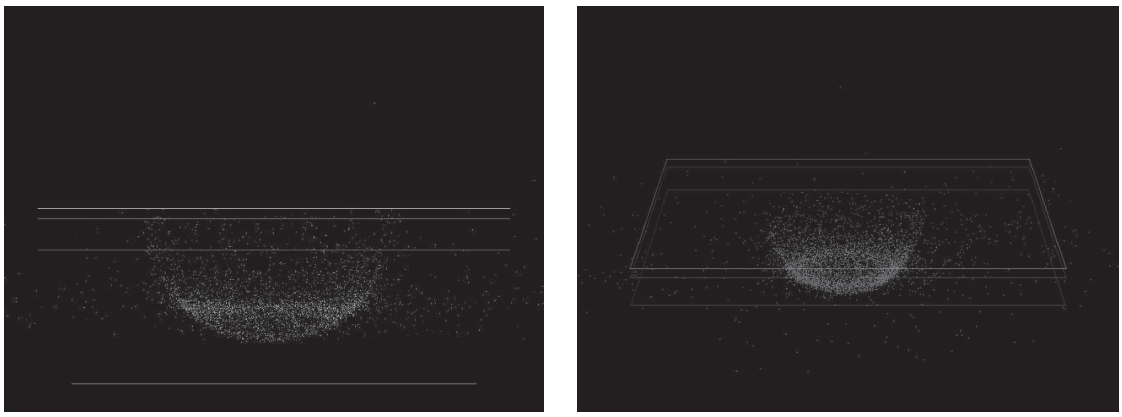

**FIGURE 1.** These stills show an EAS from a 2 TeV gamma primary as it interacts with the Milagro pond. **a)** The pond viewed from the side with the top horizontal line representing the surface of the pond, and the next two lines representing the layers of photo detectors. Almost all of the particles seen in this image are Cherenkov photons. Notice the bowl structure of Cherenkov light. **b)** The same shower from a slightly elevated perspective to clearly show the three dimensional structure of the Cherenkov light emission. Note the distinctive bowl and ring shape, not just the classic Cherenkov ring. The full color animation these stills are derived from can be seen in Web Figure 1 at http://scipp.ucsc.edu/milagro/Animations/Snowbird99.html.

as they enter the Milagro pond, each emitting light in the classic Cherenkov ring pattern (2). When the core of the shower first enters the pond, the particles' paths are coaxial and the rings of Cherenkov light from all of the particles add to form one bright ring as depicted in Figure 2. However, as the particles penetrate deeper into the detector, they suffer multiple scattering and can be deflected through large angles. The particles of the core are no longer collimated and are in fact travelling in all directions. Because of this scattering the Cherenkov rings from the particles in the core are no longer coincident, but are oriented in all directions. This scatter in the orientation of the Cherenkov rings leads to the formation of a bowl structure as depicted in Figure 3.

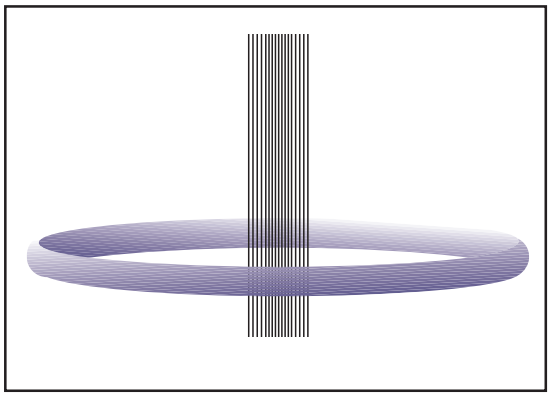

**FIGURE 2.** The particles of the EAS core are travelling colinearly as they enter the pond. The Cherenkov rings from each particle add to form one bright Cherenkov ring.

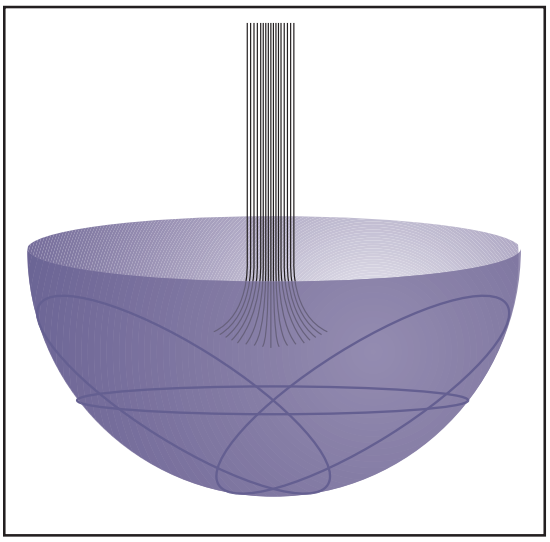

**FIGURE 3.** As the particles in the EAS core penetrate into the pond they suffer multiple scattering. This scatters the orientation of the individual Cherenkov rings. The individual rings no longer add to form one ring, but instead form the surface of a bowl. Combining the ring from when the particles first enter the pond and the bowl formed due to multiple scattering gives the bowl and ring structure observed in the computer animations.

This model very naturally describes the formation of the bowl and ring structure of Cherenkov light seen in the computer animations. When the core first enters the pond all of the emitted Cherenkov light goes into the bright ring. However, as the core penetrates deeper, multiple scattering takes over, scattering the particles of the core so that the Cherenkov light emitted forms a thin bowl instead of a ring. We can confirm that multiple scattering forms the bowl structure by returning to the Monte Carlo and creating a movie with multiple scattering turned off. This animation can be seen in Web Figure 2, where the ring is still apparent, but the bowl structure is absent.

The bowl-ring pattern applies to more than just the core. Because every particle emitting Cherenkov light will suffer multiple scattering, the probability density of Cherenkov light emission for a single particle will be the bowl-ring structure. This qualitative bowl-ring pattern is not confined to the core, but in fact describes the normal pattern of light production in the detector.

This new model for the Cherenkov emission pattern not only explains the structure

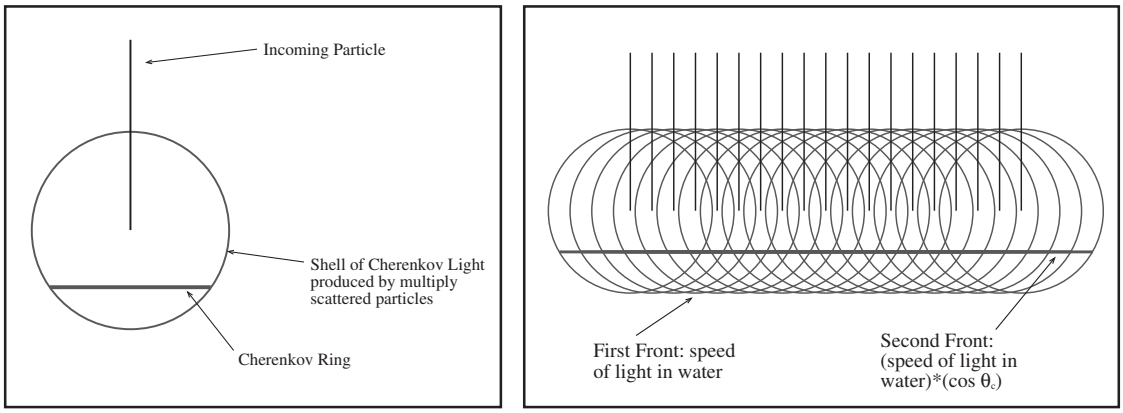


**FIGURE 4.** **a)** This diagram sketches the probability density of Cherenkov light emission from a single incoming particle. **b)** A plane particles from zenith with all emit photons in the same bowl-ring structure. The bowls add to form a leading photon front that travels at the speed of light in water. The rings add to form a secondary front that propagates more slowly. This diagram also shows that there is a lot of diffuse light that not associated with either front.

seen in the first animation, but also explains a number of other novel behaviors observed in other animations. Before looking at more animations, let's study the behavior of a shower front assuming that the new pattern of Cherenkov emission is valid.

In order to study some of the subtler effects of a shower interacting with the Milagro pond, let me introduce a simplified model of an EAS. My toy model EAS will consist of a plane of equally spaced, identical, monoenergetic particles. By removing effects caused by variations in particle density and energy with distance from the shower core, some of the more subtle effects can be easily observed.

Figure 4a shows a simple cartoon for the probability of Cherenkov emission from a single incoming particle. If we consider a plane of identical particles coming from zenith, each will emit Cherenkov light in the same bowl-ring pattern. The combination of both a bowl and ring in the emission pattern leads to the formation of two separate fronts as shown in Figure 4b. The first front is formed by the bottom of the bowls, and travels at the speed of light in the medium. The second front is formed by the rings and travels at cosine of the Cherenkov angle in the medium times the speed of light in the medium – or about 30% slower for a water based detector. This leads to bifurcation of the EAS particle front into two Cherenkov photon fronts – one for the bowls and another for the rings.

Now let us consider another toy model EAS incident at an angle as depicted in Figure 5a. Again the bifurcation of the shower front and the late light are apparent, but the second front is much broader than in the shower from zenith. This is because the Cherenkov rings are coaxial with the incoming particles, not the refracted shower fronts. The rings stack like dominoes when the shower is incident at an angle, and only fully overlap for a vertical shower. This stacking leads to an angle dependent broadening of the second Cherenkov light front.

All of these effects can be seen through close examination of Figure 5b, showing a full Monte Carlo simulation of a toy model EAS incident at an angle. The refraction is

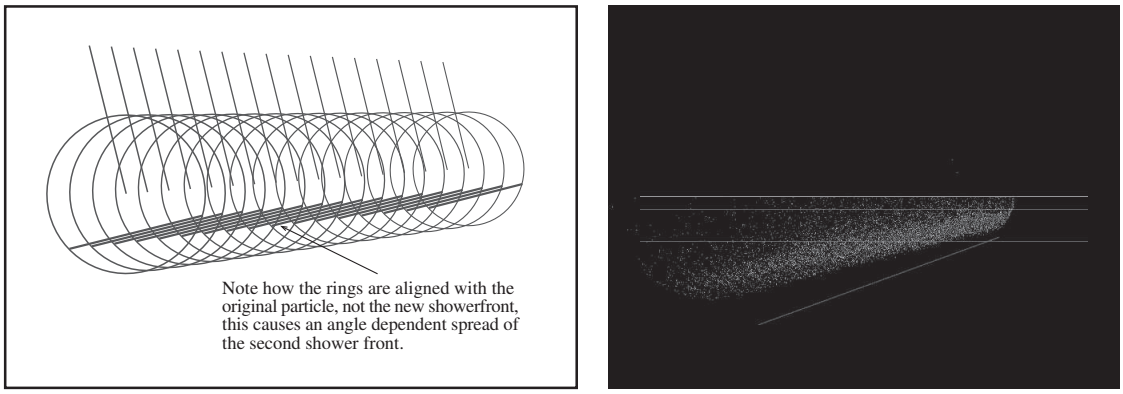


**FIGURE 5. a)** Depicts a toy model EAS incident on the pond at an angle. Note again the double front, with the second front showing angle dependent smearing. **b)** A still from a full Monte Carlo animation of the toy model EAS. The angled line shows where the particles of the EAS would be if they had not encountered the pond. Close examination of this image shows the refraction, bifurcation, and angle dependent smearing predicted by the bowl-ring model of Cherenkov light emission. The full animation can be seen in Web Figure 3.

clearly apparent, with close study revealing the second shower front. Web Figure 4 shows the same simulation without multiple scattering to isolate the second front and clearly show the angle dependent spreading.

The qualitative bowl-ring model of Cherenkov light emission explains both the formation of the bowl structure seen in the full EAS simulations, and the refraction, bifurcation and angle dependent spreading of the Cherenkov light fronts. This model gives us a much more robust understanding of the EAS-pond interaction, and will allow us to develop more effective automated data analysis routines.

## Conclusion

Computer animation techniques are a powerful new way of analyzing experiments and the interplay of subtle physical effects. By applying animation techniques we were able to observe several unexpected phenomena, and to develop a new model that better explains the interaction of an EAS with the Milagro detector.

## REFERENCES

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2. Jackson, J.D., *Classical Electrodynamics, Second Edition,* New York, John Wiley & Sons, 1962, pp. 638-641.