The world unseen: Photography as a probe of particulate materiality

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Abstract

This article examines the role of photography in the scientific discovery of cosmic radiation and antimatter, showing how a visual medium designed to react to photons was successfully coopted to detect invisible particles and antiparticles through traces left by their collision, so-called annihilation events. The continuous presence of cosmic radiation means that every photograph is always already a double image, carrying both a visible surface formed by photons and a latent image carrying traces of cosmic rays, the latter 'image' continuing in its perpetual state of 'development'. It is the physical irregularity of the photograph exposed to the continuous and uniform shower of cosmic radiation that leads Doser to speculate on image formation not through an external referent but through the internal manipulation of the material substrate.

Keywords

Antimatter

astrophotography

cosmic rays

particle acceleration

annihilation

latent image

An etymologically minded individual might legitimately equate photography with drawing with light. And indeed, historically, photographic emulsions have been developed with such photosensitivity in mind, with the desire to record permanently, as in a drawing, that which the eyes see (thanks to reflected, focused and detected photons in the eye's retina's cones), albeit evanescently. In spite of its sophistication, the human eye is however quite limited, not only in the range of frequencies, brightness, and duration, but also in the type of radiation it can detect. It is blind to microwave, infra-red, ultra-violet or gamma-ray wavelengths, unable to detect extremely faint light sources, insensitive to very rapid or very slow intensity variations, and in spite of being ubiquitous, elementary particles are invisible to the eye. Photography goes well beyond physiology in two major ways. First, it transforms a transient process (photons triggering electrical pulses on the retina's cones) into an integrative one: further photons, even if their instantaneous rate were to lie below the optical threshold of the eye (but above the level needed to form a latent image [Maerker 1954]), will gradually increase the fraction of darkened grains, and thus allow a sub-threshold image to be captured. Second, by appropriate choice of filters and/or photosensitive molecules, it introduces the conceptual ability to expand the range of recorded wavelengths beyond the range accessible to the eye's photoreceptors.

Nevertheless, there are wide swaths of reality that remain hidden from observation if one sticks even to this broadened definition of photography. Technological developments at the end of the nineteenth and the beginning of the twentieth century – driven among others by the fields of astronomy and nuclear physics – allowed photography to expand its range dramatically into these hitherto invisible areas: on one hand, the time-integrating nature of photography was disrupted, and temporally varying elements identified which would transform photography into a ruler with which to measure the Universe; and on the other hand, by considering the photographic plate no longer as a plane, but as a three-dimensional sensitive volume, photography gained a spatial component that would allow it to be used to explore the subatomic frontier. But equally, expansion of photography into those realms provides a framework to shed light on the meaning of photographic reality.

In the first case, photometry provided a way to study extremely faint astronomical objects, both detecting them, as well as reliably documenting their temporal variations. In spite of numerous challenges (unknown wavelength response of photographic plates, variable seeing conditions and non-linear relationships between illumination and emulsion darkening), in a decade-long painstaking effort, the pioneering astronomer Henrietta Leavitt discovered scores of variable stars (2008) and, more importantly, focusing on the Small Magellanic Cloud (Figure 1a), discovered in 1912 a relationship (Figure1b) between the periodicity of these stars and their luminosity (Leavitt and Pickering 1912), which provided the first 'standard candle' with which the size of our galaxy, and ultimately of the Universe, could be established. [place Fig. 1 here]

Almost at the same time, expansion of the range of sensitivity of photographic plates was driven by the need to identify the nature of the then mysterious cosmic rays, which in turn were discovered by pursuing an earlier mystery (Hess 1912). It had been observed that a device called an electroscope, which measures the presence of charged particles, such as electrons, slowly lost its charge over time, and careful experiments by William Crookes in the late nineteenth century showed that ions present in the air were the cause. Something was ionizing the neutral atoms and molecules, and producing these charged ions. A number of physicists explored different hypotheses to elucidate this mechanism, among them Victor Hess. Hess speculated as to whether the source of ionization (as recorded by the discharging over time of electroscopes) could be located in the sky rather than the ground, as assumed by many. In preparation to testing this idea, he ascertained that any radiation originating from Earth-based sources would become negligible above a height of 500 m above the ground, and ensured that his instruments would not be adversely affected by changes in pressure or temperature. In a series of balloon flights in the years 1911 to 1913, several of them at night and one, on April 17, 1912, during a partial solar eclipse (to exclude any solar origin of the ionizing radiation), he then measured the ionizing radiation, and observed during his ascents that after initially decreasing with increasing altitude, the radiation subsequently strongly increased, reaching values many times at altitudes of several miles greater than at ground level. From this, he concluded that 'a radiation of very high penetrating power enters our atmosphere from above' (Hess 1912).

This radiation was made visible by photography; in the 1920s and early 1930s, Marietta Blau (Sime 2012) developed photographic emulsions with sufficient sensitivity and thickness that the ionization induced by elementary charged particles flying through them could be recorded as a discontinuous line of blackened AgBr grains. Of crucial importance was the fact that photographic emulsions could integrate signals over many weeks or even months, a major advantage over cloud chambers or scintillating counters, whose images are highly evanescent. Her first success was the detection of protons (Blau 1925), followed by application of this technique to detect neutrons (Blau and Wambacher 1932). The major breakthrough that this technique allowed however was in the study of cosmic rays. By exposing stacks of thick emulsions over weeks at high altitudes (where the cosmic ray flux is significantly higher than at sea level), she managed not only to image numerous cosmic ray tracks, but identified a few very rare instances in which a cosmic ray crashed into a nucleus of Ag or Br in the emulsion, and caused a burst of nuclear fragments to spray through the photosensitive volume (Figure 2). This discovery of cosmic-ray induced nuclear spallation (Blau and Wambacher 1937) triggered intense interest; to investigate this process in detail, a number of systematic experiments with different target nuclei were initiated by her, but tragically, her forced emigration from Austria on the eve of annexation by Nazi Germany brought these to a halt before they could be completed. [place Fig. 2 here]

The development of particle accelerators in the following decades provided many opportunities to apply specially formulated photographic emulsions, so-called nuclear emulsions with a high sensitivity to minimally ionizing particles, to the fields of nuclear and particle physics. One of the most spectacular applications was in the detection of the first antiprotons to be artificially and intentionally formed at the Bevatron in Berkeley in 1955. Antimatter annihilates upon contact with matter, transforming the full mass of the disappearing particle and antiparticle into energy, which can then re-appear in the form of new particles and antiparticles; if this annihilation takes place on the surface of a nucleus, some of the annihilation energy can also split apart the nucleus, producing nuclear fragments. For annihilation to occur, there has to be either a collision between the incoming antiparticle and some nucleus of the target material (very unlikely, given the tiny size of nuclei relative to atoms), or else the antiparticle has to shed its kinetic energy before it can approach the nucleus sufficiently slowly for it to interact with it. The first image of an annihilating antiproton (Figure 3) thus contains both the trace of the antiproton slowing down from relativistic speeds, as well as spallation fragments and subatomic particles formed in the annihilation process itself. The one incoming, and nine outgoing traces can be considered as a three-dimensional record of the passage of the particles. On the time scale of a photograph, the process is instantaneous, with the complete exposure happening within less than 0.1 ns, while the chemical transformations within the silver halide grains involved in latent image formation occur on a much slower time scale, of up to tens of microseconds (Berg 1947), and the more standard gradual accumulation of photon-induced changes within the grains lasts even longer, the full duration of an exposure, from ms to many seconds.

[place Fig. 3 here]

But it is also possible to produce lower energy antiprotons, which no longer need to be slowed down, and consequently annihilate immediately upon contact with the uppermost layer of the emulsion, without leaving an incoming trace, the point of annihilation lying at the confluence of all the resulting fragments (Figure 4a). And finally, one may choose to annihilate the antiproton in a microscopically thin layer just above the photographic plate, in which case not even the point of annihilation is visible, but only the stubs of the tracks stemming from the annihilation, whose presence is inferred, rather than being directly visible, by extrapolating the stubs to an invisible common origin (Figure 4b). [place Fig. 4 here]

These photographs raise a number of intriguing questions about the nature of photography, and what is meant when talking of an image, or even of seeing.

When photographing with light, the photons that form an image are those that have interacted with the object whose image is being recorded ('La photo est littéralement une émanation du référent' [Barthes 1980]), and these photons disappear, in a certain way, into the grains that they change chemically. On the contrary, the subatomic particles have not 'bounced off' an object to be imaged, but have instead pursued a trajectory through both the object as well as through the emulsion, and can not even conceptually be considered to still be (virtually) present in the grains that they have contributed to darken; the photograph is a lingering memory of their passage.

Photons originating from an object in motion will end up in different points on the film, but these positions do not correspond to the positions of the original object; reconstructing those from the position of an exposed grain would require knowledge of the full geometry of the recording apparatus, including all optical elements. With ionizing radiation, the situation is different and far simpler: the position of the exposed grain corresponds exactly to the position of the ionizing particle at a certain point in time, and the aggregation of darkened grains maps out in a single combined image the full spatio-temporal sequence of a particle, a 'bullet-time' representation of its trajectory. An analogy would be that of a time-lapse photograph of an unchanging landscape, through which an individual walks; the resulting picture would show a static scene, through which a human-shaped tunnel-tube winds, all positions taken by that individual over time forming a single sculptural entity.

The black lines and dots are of course not images of the particles themselves, but rather indirect traces of their passage, AgBr grains that were exposed long after the ionizing particles have left the emulsion, by remnants left in their wake. Since the photosensitive grains in the emulsion are also sensitive to electrons, it is these, rather than any light, that produce a darkening of the emulsion when charged particles traverse the emulsion, ionizing the atoms on their trajectory. These are, furthermore, not planar images; instead, they form a three-dimensional structure, a series of blackened pearls strung out in space or of black branch-like lines, vastly expanding the microscopic trajectory of the subatomic particles themselves. One thus has both a temporal and a dimensional shift:

the photograph is a flash-frozen time-delayed bulimic memory of the three-dimensional path taken by an invisible entity over time.

Nevertheless, these images at least correspond to a physically real system, to objects that, in concept, if not in reality, could be tracked and followed, and for which the trajectories recorded photographically (in their full spatiality) can be conflated with the trajectories actually followed by the particles in space. In that sense, it is legitimate to talk of 'photographs of particles'. But what of photographs involving antimatter, the mirror image of matter predicted by Dirac in 1928, and discovered only a few years later in cosmic rays by Anderson? Just like matter, antimatter consists of (anti)particles, whose charge is the opposite of the corresponding particles, negatively charged antiprotons instead of positively charged protons, positively charged antielectrons instead of negatively charged electrons.

As is the case with matter particles, antiparticles are recorded indirectly, via the electrons liberated from the atoms in the emulsion that they traverse prior to coming to a stop (or, if their initial energy is low enough, they stop already at the surface of the emulsion, without leaving an incoming trace). Once stopped, they annihilate with a proton or a neutron in a nucleus (in the case of an antiprotons) or an electron (in the case of a positron); they cease to exist. Instead, new particles and antiparticles appear, in the form of photons or of so-called mesons, possibly accompanied by nuclear fragments that are ejected as a consequence of the annihilation process' vehemence. The charged particles again ionize atoms in the emulsion, and are seen indirectly; the photons – whose energy is far higher than that of light in the visual spectrum – can at best be detected if they transfer part of their energy into an electron of an atom in the emulsion, which will then in turn ionize further atoms along its trajectory, and at worst will leave the emulsion without leaving any further trace.

This is an attempt to record a disappearing act. The image, while clearly identifiable as a 'starburst', is a doubly indirect way of imaging an annihilation: not only are all the traces only indirect recordings of particles' passages through the emulsion, but the annihilation itself is merely inferred from the geometry and the characteristics of the resulting secondary particles. What is being photographed is the aftermath of a disappearance that takes place within the emulsion. This absent referent has in fact disappeared before any conceivable shutter could be opened; it is the bark in the night without a concomitant dog, whose 'death', instead of being in the future past, as is the case in other photographs ('je frémis, tel le psychotique de Winnicott, d'une catastrophe qui a déjà eu lieu. Que le sujet en soit déjà mort ou non, toute photographie est cette catastrophe' [Barthes 1980]), has already taken place.

If however the annihilation takes place above the emulsion, in a foil thin enough that the secondary particles may reach the photographic plate, and thus leave their traces as they traverse it, a further layer of abstraction is attained, since there is no longer a clearly recognizable signature corresponding to the annihilation, there is no longer an identifiable and visible annihilation 'starburst'. Instead, the disappearance is inferred via the appearance and composition of the resulting radiation in form of radial stubs of different blackness and tenuousness that induce the viewer to imagine the shared origin; the image of the annihilation (which our eyes could never see) is obtained by interpolating extrapolations from that which is recorded indirectly, a virtual image conflating a complex dynamic process into a single static sculptural structure.

The interplay between the concept of exposure, of latent image and of developing a latent image can also be explored with particles. In the images of Figure 4a and 4b, the photographic film had already been exposed to particles (background radiation in form of cosmic rays, as well as intentionally produced neutrino beams), and thus potentially contained multiple latent images of charged particles, before the film was reconditioned, and exposed to antimatter annihilations. Within these images thus (very likely) lie ghosts of previous particulate realities that have been resorbed. In fact, since cosmic rays continuously traverse any object that is not shielded by many km of rock or water, ordinary photographs simultaneously contain both the image induced by light as well as a fragmentary presence of minute traces of particulate matter, visible at best as individual darkened grains among a multitude.

While the image produced by light is unevenly spread out over the plate, cosmic rays expose the plate evenly and uniformly. An emulsion that would be stored in the dark over an extended period would exhibit – after development – a fully black image, unless this incessant exposure to cosmic rays were somehow modulated by material that absorbs or scatters cosmic rays. In that case, what would appear is the shadow, in cosmic rays, of the object lying above, similar in concept to images taken in x-rays, which can expose the emulsion, but only where their path is not blocked by dense matter. The shadows cast by an invisible object via invisible forms of radiation onto the photographic plate forms a vivid shadowgram, a complex image that allows determining either the characteristics of the invisible masking object (in case the illumination is uniform), or of the illuminating source (in case the masking objects characteristics are known). Similar to contact prints, such patterned ('coded') masks (Dicke 1968), through their spatially selective absorption and transmission (Figure 5), together with the resulting spatially varying intensity distribution produced by high-energy gamma rays or cosmic rays on the photographic detector plane, allow mathematically reconstructing the undistorted original image. [place Fig. 5 here]

It is of little matter here whether the gamma rays or cosmic rays are then detected via darkened grains in an emulsion, or via electronic signals in a CCD; what is important is that they have passed through a superposition of pinholes belonging to a superposition of camera obscuras, and that this redundancy allows deconvolving the recorded image. In this way, cosmic ray radiography becomes possible (Morris 2014), allowing 'photographing' the invisible interior of e.g a hollow lead sphere (Figure 6), but also of nuclear reactors (Perry 2013), of ancient pyramids (Rhodes 2015) or even of very large natural structures such as volcanoes (Cârloganu 2013). [place Fig. 6 here]

In all of these images, however, the origin of the image is *external*; the photographic plate *receives* the image, a projection of the complex three-dimensional world onto the thin layer of the emulsion, in which all grains are equal. The intensity modulations of the image result in a spatially modulated distribution of the darkened grains. It is however conceivable that the photosensitive grains themselves could be manipulated prior to exposing them, drawing not with light but through the spatial variations of grains' sensitivity. Exposure to a uniform flux can then reveal a 'latent' image intentionally included in a seemingly isotropic emulsion, resulting in a carefully crafted artificial photograph. Since cosmic rays illuminate objects uniformly, it is natural to contemplate how this illumination can – in combination with some aspects of photosensitive grains – be used to transform a continuous, if invisible, radiation into the materiality of a differentiated photograph. The dual requirement of undifferentiability of the 'latent' image prior to exposure, and of using cosmic rays to carry out the process of fixing or revealing this image can be met by considering atomically identical isotopes: carbon dating relies on the transformation in the atmosphere of ^{14}N (stable) into ^{14}C (radioactive, with a decay life time of 5730 years) through cosmic rays. The ratio of the carbon isotopes (dominantly ^{12}C, about 1% ^{13}C, and a tiny admixture of the continuously formed and continuously decaying ^{14}C [Coplen 2002]) that a living organism absorbs from its environment will start changing at the moment of death, with the fraction of the radioisotope exponentially decreasing, until after many millennia, only the stable isotopes remain. Inversely, exposing a (pixelated) image, whose pixels consist of carbon devoid of ^{14}C, as is the case for ancient carbon that has been protected from cosmic rays through rock over eons (with a natural ratio of 99% ^{12}C and 1% ^{13}C) or for mass-selected carbon (purified to contain only ^{12}C), to the action of cosmic rays entails an interesting temporal evolution. Any decaying ^{14}C will – through its decay – produce locally ionizing radiation, and thus lead to a localized darkening of the emulsion below the pixels containing ^{14}C. In the absence of cosmic rays, all pixels containing only ^{12}C or a mixture of ^{12}C and ^{13}C will remain light. Cosmic rays will however, over time, transform ^{13}C into ^{14}C (albeit with a very low likelihood). In other words, those pixels containing ^{13}C will very gradually darken. In the (very) long term, however, cosmic rays can also transmute ^{12}C into ^{13}C (Oppenheimer and Phillips 1935), thus transforming the potentially inactive pixels into active pixels, although for that to happen, the second transmutation of the formed ^{13}C into ^{14}C (Curling and Newton 1950) must still take place subsequently.

It is tempting to apply this alchemical concept to a photographic emulsion covered with bitumen of Judea, using both naturally occurring bitumen ('ancient' carbon) or synthesizing bitumen from mass-purified ^{12}C ('pure' $^{12}CO_2$), and to 'paint', pixel by pixel, a view of village houses, such as might be seen through a window in the south of France, for example in the village of Le Gras. The initial image will be invisible; the emulsion would be undifferentiated. As long as the plate is protected from cosmic rays, deep underground, the image will remain latent. If however no such precautions are taken, the ‘ancient’ pixels, whose ^{13}C is slowly transformed by cosmic rays into the electron-emitting ^{14}C radioisotope, will gradually darken the underlying emulsion, so that after a very long time, a second latent image will gradually appear in the emulsion. Not even this image is however eternal: after even longer times, with all pixels gradually coming to contain ^{14}C, which consequently will darken the underlying emulsion everywhere, an evenly blackened (latent) image will ever so slowly emerge. At this point in time, the natural equilibrium of the different carbon isotopes is again achieved, forever hiding any putative photographer’s intervention.

In the end then, how can one know if the resulting image was formed by patterned light falling onto a uniform photographic film, or by uniform illumination of a previously skillfully patterned emulsion?

Figures

Figure 1a: Separate graphs for maximum and minimum Cepheid magnitudes, with Period in days (logarithmic scale) on horizontal axis and apparent magnitude on vertical axis (Leavitt and Pickering 1912).

Figure 1b: Astro-photograph of the Small Magellanic cloud (Leavitt 1908).

Figure 2: 'A "star" with eight tracks is reproduced. On account of the rather steep angles at which some of the particles cross the emulsion-layer (approximately 70 micrometers thick) it is not possible to have all of the tracks of a 'star' in focus simultaneously'. Reprinted by permission from Macmillan Publishers Ltd: (Blau and Wambacher 1937) (http://www.nature.com/nature/journal/v140/n3544/pdf/140585a0.pdf)

Figure 3: This first image of an annihilation star, found in the photographic emulsion stack experiments led by Gerson Goldhaber of the Segrè group, confirmed the discovery of the antiproton. An antiproton enters from the left of the image and travels about 430 micrometers before meeting a proton. Nine charged particles emerge from their mutual annihilation. Reprinted with permission from *Physical Review*. Copyright (1956) by the American Physical Society (Chamberlain et al. 1956).

Figure 4a: (Top) Typical antiproton annihilation vertices in the bare emulsion as studied by the AEgIS collaboration (Doser et al. 2012).

Figure 4b: Tracks observed behind a thin silver foil in which the antiprotons annihilate (Kimura 2013).

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Figure 5: Scatter hole camera. The entrance plate is randomly perforated to provide randomly positioned pinholes. The image is recoded photographically, photoelectrically or with a photon counter such as a wire spark chamber. Copyright AAS. Reproduced with permission (Dicke 1968).

Figure 6: Image of a hollow lead sphere via cosmic rays. This image was published in Christopher Morris et al. (2014), Copyright Elsevier. Reproduced with permission.

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Figures:

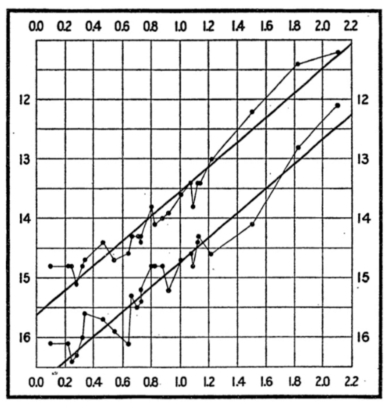


FIG. 2.

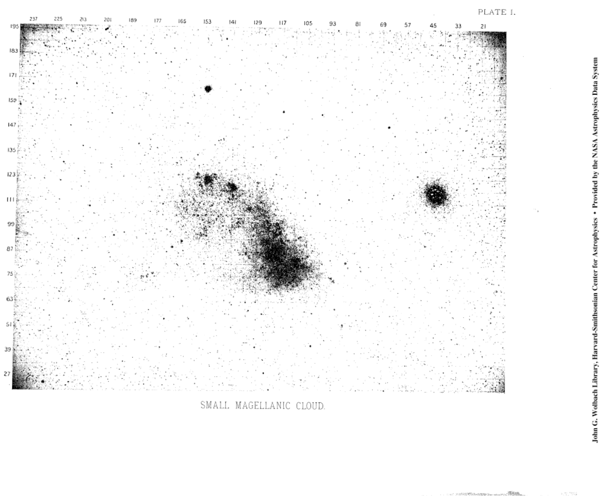
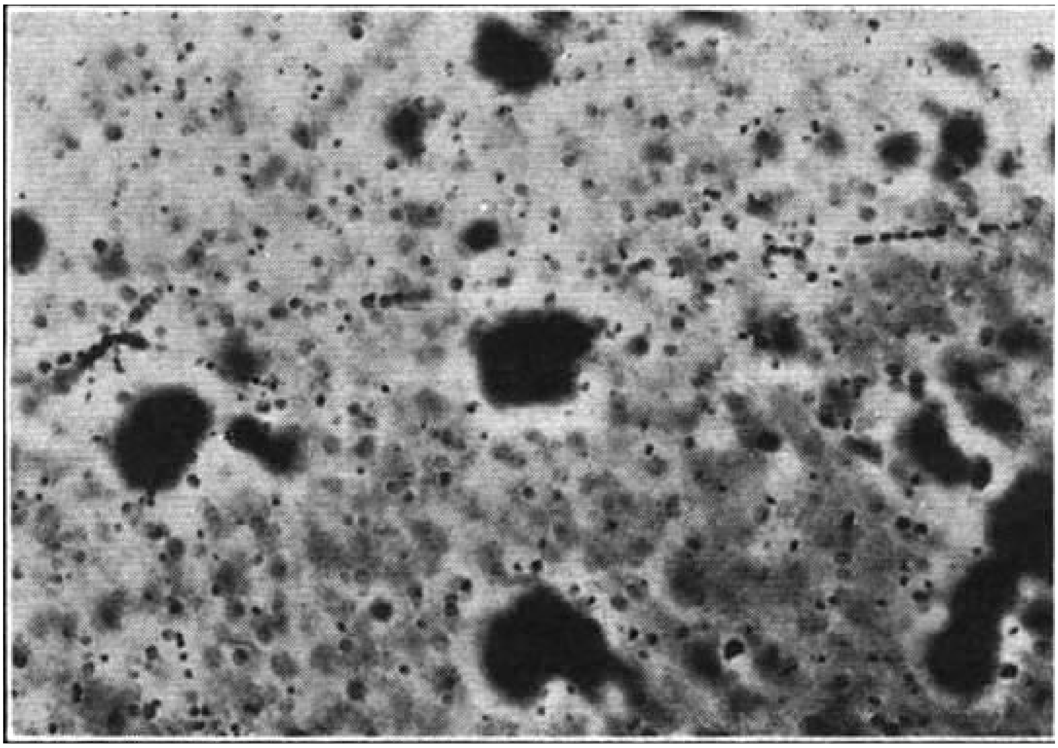


Fig. 1a: Separate graphs for maximum & minimum Cepheid magnitudes, with Period in days (logarithmic scale) on horizontal axis & apparent magnitude on vertical axis. [Leavitt12]

Fig. 1b: Astro-photograph of the Small Magellanic cloud. [Leavitt08]



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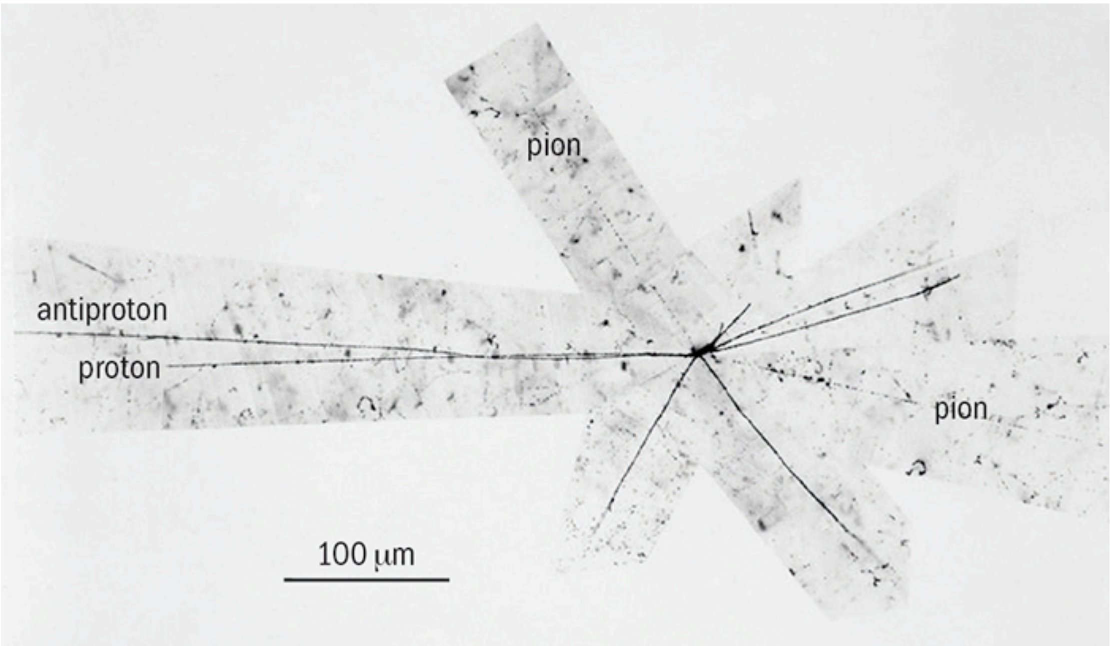

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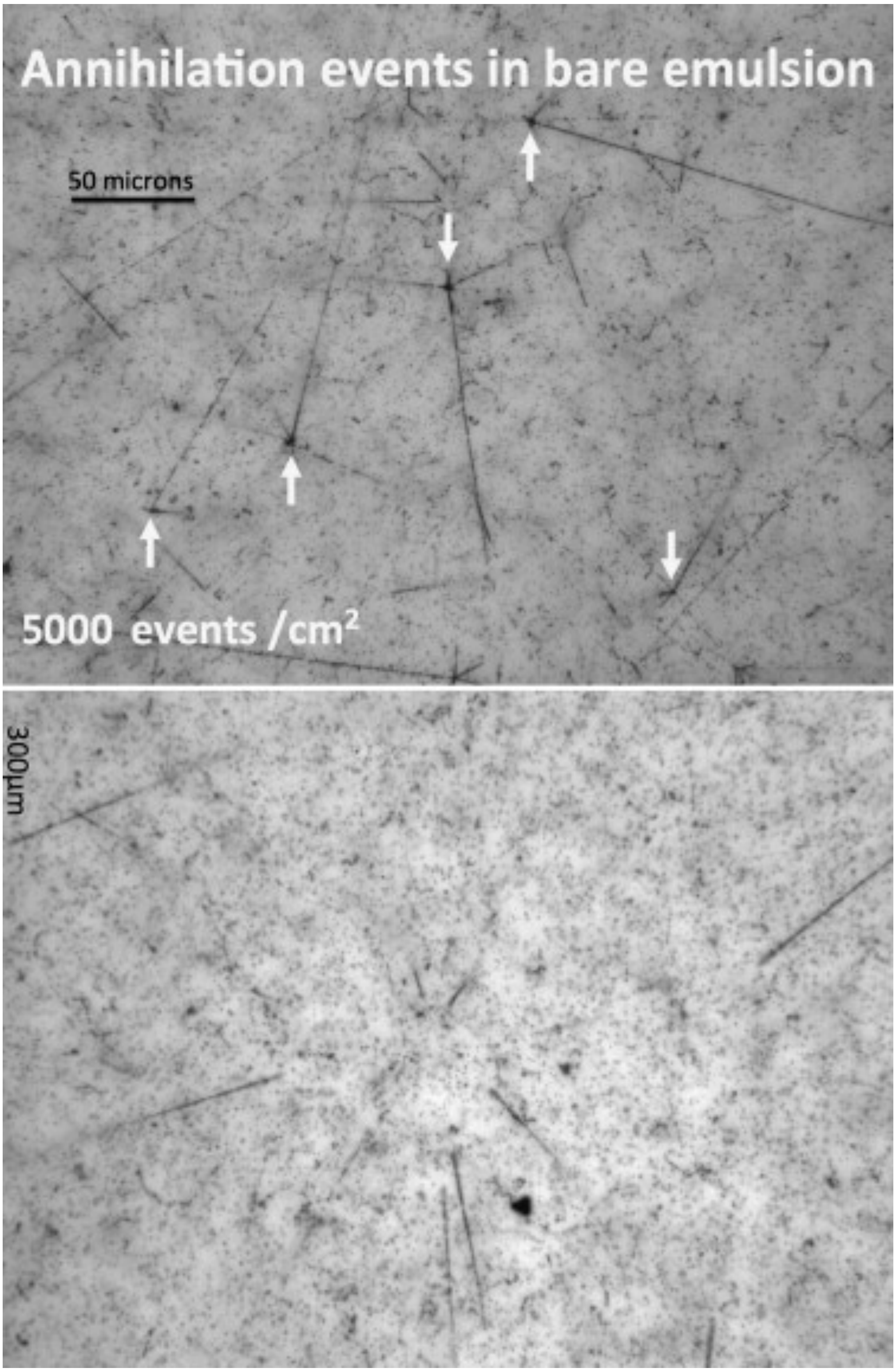


Fig. 4a (Top): Typical antiproton annihilation vertices in the bare emulsion as studied by the AEgIS collaboration [Aegis12].

Fig. 4b (Bottom): Tracks observed behind a thin silver foil in which the antiprotons annihilate. [Aegis13]

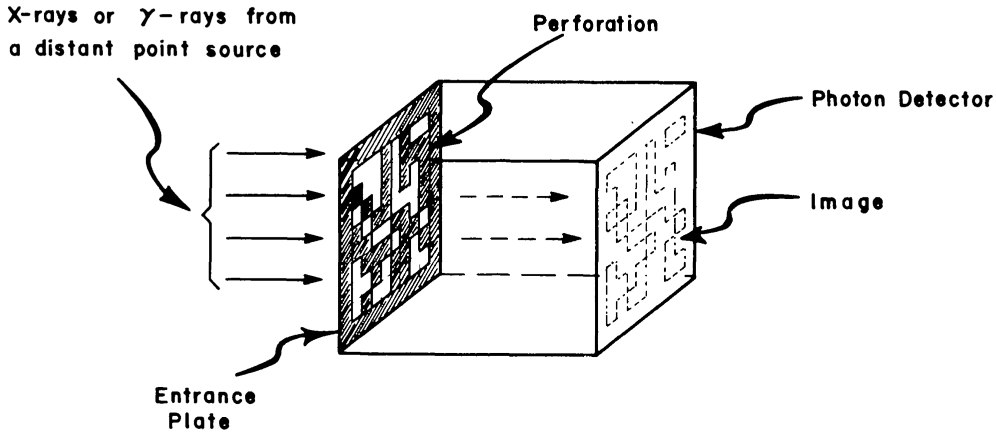
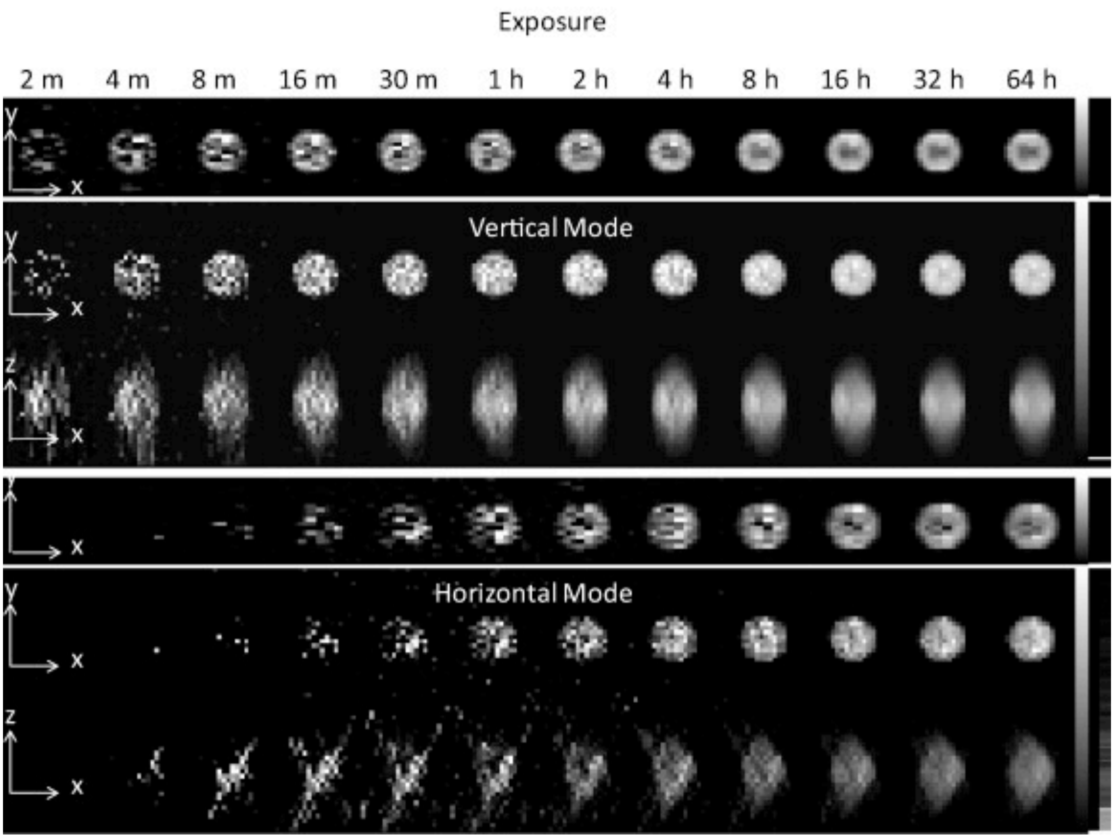


Fig. 5: Scatter hole camera. The entrance plate is randomly perforated to provide randomly positioned pinholes. The image is recoded photographically, photoelectrically or with a photon counter such as a wire spark chamber. © AAS. Reproduced with permission [Dicke68]



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