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A charged particle telescope—a proposal

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Abstract

We propose the construction of a telescope, which uses charged particles (CPs) instead of light in order to study the dynamics of the astronomical objects. We have indicated the obvious incentives for such a project. Using CPs instead of electromagnetic radiation, astronomers would finally have the necessary tools to study the evolution of the astronomical objects. We demonstrate that there are no insurmountable obstacles for building such a CP telescope.

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1. Introduction

In the January 2002 issue of Scientific American, Reynolds [1] published a spectacular 3-page panel showing how our Milky Way galaxy looks from our vantage point, when imaged by telescopes using radiation from different parts of the electromagnetic (EM) spectrum. These images, made with rays ranging from radio waves to gamma rays, reveal a wealth of information which is pivotal in understanding our galaxy. The dramatic images produced by telescopes are at the forefront of space exploration.

Those of us who work in charged-particle optics (CPO) might want to think about the possibility of a role for CPO in space exploration. It is known that charged particles (CPs) with a wide range of kinetic energies abound in space [1,2],[1] and the expertise to design a CPO telescope exists, but it is not known whether or not the information carried by a CP beam, or the beam itself, could survive the rigors of the trip through space from the object to the telescope. Perhaps the most advanced instrumentation for studying the CPs and magnetic fields is the RAPID imaging spectrometer on board Cluster [3]. It uses a pinhole to obtain a crude image or a distribution of the incident particles. The total sky is divided into 196 pixels providing the distribution. This distribution shows substantial detail at the resolution of 196 pixels. The fact that this is possible, suggests that the electrical or magnetic fields encountered and the scattering by particles is not too severe to erase all the information, and imaging is a possibility. The

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[1] See for instance the Charge, Element, and Isotope Analysis System (CELIAS) webpage at http://www.cx.unibe.ch/phim/soho/.

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magnetic field in fact, could be an asset in guiding CPs through space, because the particles travel mainly along the field lines, rather than at right angles to them. This phenomenon is illustrated at a very different scale by a technique in electron microscopy, where the specimen is placed in a strong magnetic field. The electrons emitted from the specimen diverge along the field lines to form a magnified image of the specimen surface [4].

Assuming that CP beams are suitable for imaging, are there any incentives for building CP telescopes (CPTs)? We (the authors) are not astronomers, so our discussion of this question is based on a limited view of the challenges of space.

Generally, when a new method of imaging is introduced, new information is revealed. The existing telescopes use EM radiation for imaging, and the images produced with different parts of the spectrum have strikingly different intensity distributions. A telescope using CP radiation could provide still another basis for contrast in the image, since the intensity distribution would in this case depend on the spatial distribution of CPs issuing from the object. In the special case when objects are too cool to emit EM radiation, they could perhaps be imaged by means of CPs ejected by X-rays or high-energy particle bombardment.

Another way in which CP imaging could reveal new information has to do with the speed with which the radiation travels through space. The radiation used by the existing telescopes travels at the speed of light c, whereas the CPs travel at speeds v dependent on their masses and kinetic energies, always less than c. Hence, CP rays would have to leave an object earlier than would EM rays in order for the two types of rays to arrive simultaneously at their respective telescopes. Assuming that information is imprinted on CP beams, as it is on light beams, the CP image would correspond to an earlier time in the history of the object than would the EM image. Consider, for example, the famous supernova remnant, the Crab Nebula that was seen to explode in 1054 AD. The Crab Nebula is about 6500 light years away, so that the image that is formed by a light telescope would correspond to the object as it was 6500 years ago and 948 years after the explosion. If the Crab Nebula were imaged by, say, electrons with $v/c = \frac{1}{3}$ (28.6 kV beam voltage), the image would correspond to 19, 500 years ago, or 13, 000 years earlier than the date of the light image. One could therefore obtain information about the star prior to its explosion! Thus, by imaging electrons having lower energies we could look farther back in time. In a flight of fancy, one could imagine following the history of an object (prior to the date of the light image) by imaging CPs of successively higher energies.

The exploits referred to in the previous paragraph would necessarily require a beam of CPs with a sufficiently large range of energies. A simple uncorrected telescope can form sharp images with beams having narrow energy ranges such as are used in electron microscopy and focused-ion-beam applications. If the energy distribution is wide, only CPs having the narrow energy range for which the telescope is focused will form a sharp image. Because of chromatic aberration, CPs having energies outside this range will form unfocused images. The unfocused images will superimpose on the focused image and may obscure it, unless the telescope is focused on a strong peak in the distribution.

2. Experimental set-up and results

In an electron bench experiment, a simple uncorrected electrostatic telescope was set up to study the individual images obtained with various amounts of defocus. A narrow energy-range beam was used. The telescope consists of an objective lens and an “eyepiece”. The eyepiece is made up of a field and a projection lens. The object for the telescope is a fine mesh, transmitting electrons from an upstream electron source. The objective lens focuses a demagnified image approximately at the field lens, and the projection lens projects a magnified image onto a phosphor-coated fiber-optics window. The image is recorded by pressing a photographic film against the exterior face of the window. The electron bench set-up is shown in Fig. 1.

The lenses used for the telescope are einzel lenses with three electrodes. Two lenses, like the one shown in Fig. 2, are used face-to-face for the

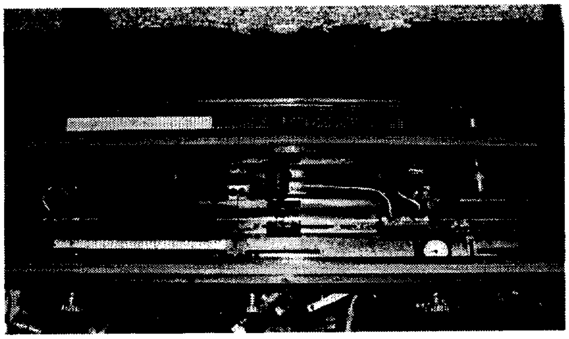


Fig. 1. CPT simulation in the electron-optical bench. The telescope's objective lens is near the center of the vee-way. The two lenses which make up the eyepiece are to the right. To the left on the vee-way are the condenser lens, followed by the housing holding a 2000 lines/in. mesh, the object for the telescope. The electron gun is mounted at the left end of the bench, and the fiber optics window, (not shown) is at the right end of the bench. Aligning screens and mu-metal screens have been removed for clarity.

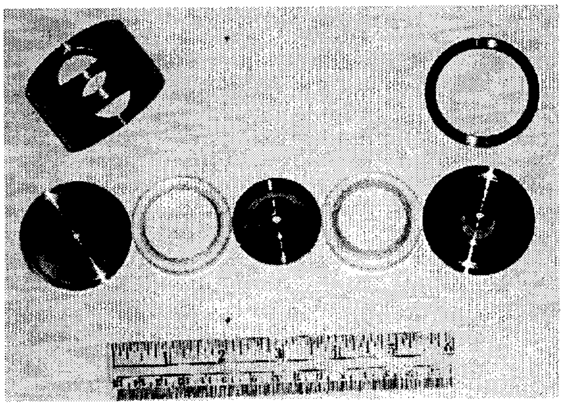
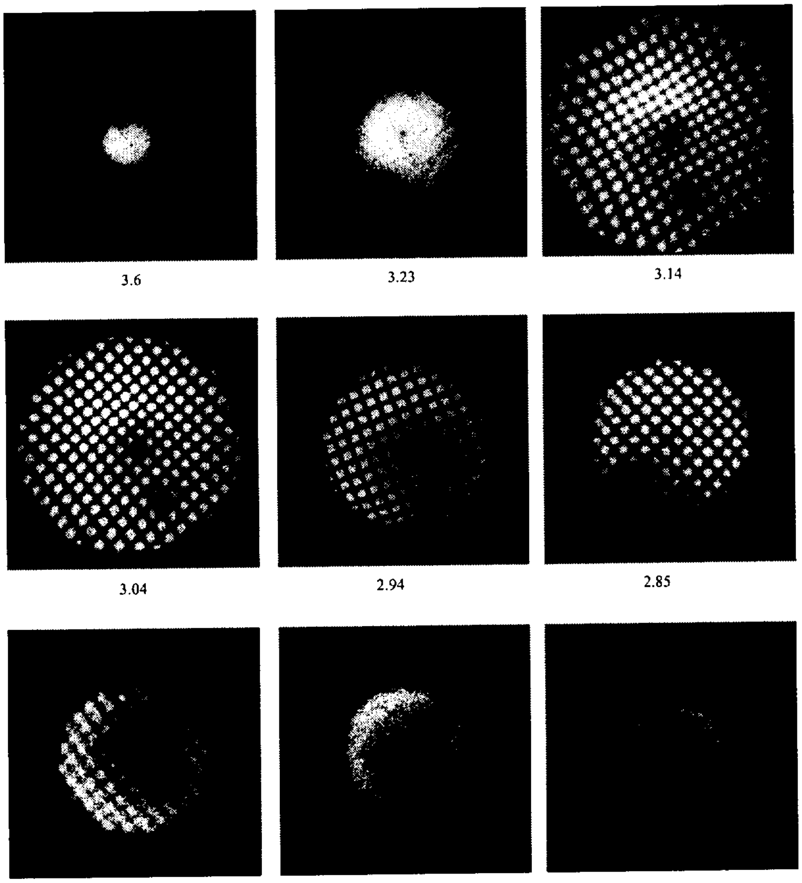


Fig. 2. An electrostatic lens used as part of the telescope eyepiece, shown disassembled. The electrodes, made of naval brass, are shown in the lower row along with rexolite insulators. The housing and retaining ring are shown in the background.

eyepiece of the telescope; the objective lens is similar, but with larger apertures, inter-electrode spacings, and thickness of the center electrode. These lenses were existing lenses, and were not designed specifically for this project. The lenses are operated with the center electrodes at a negative potential V_L, and the outer electrodes at ground potential. The voltages for the telescope lenses are obtained from taps on a voltage divider. An adjustable power supply provides high voltage to one end of the divider, the other end being grounded. A thermionic triode electron gun provides the electron beam; a condenser lens is used for collimation. For this experiment, the voltages for the gun and condenser lens were obtained from a separate power supply and voltage divider.

The focusing power of the lenses depends on the ratio of the voltage $-V_L$ between the lens electrodes, and the beam voltage $V_B = -V_C$, where V_C is the potential of the electron gun cathode (negative). In the experiment, the beam voltage remained constant at 20 kV, and the voltage ratio was changed by changing the telescope voltages rather than the beam voltage. This was done to ensure that the beam current would be the same for different settings. The settings are labeled by the ratio V_C/V_1 for the objective lens, L_1. An increase in this ratio corresponds to a weaker lens or, equivalently, to a higher beam energy. The beam voltages for the other two lenses L_2 and L_3 are given by $V_2 = 1.13V_1$ and $V_3 = 1.23V_1$. A series of images was recorded over a V_C/V_1 range of from 3.6 to 2.6. (The high values of V_C/V_1 reflect the fact that the lenses were designed for tighter focusing than was needed in this application.) Selected images are shown in Fig. 3. The in-focus undistorted image is at the center, labeled with a voltage ratio of 2.94. For higher and lower voltage ratios, the figure shows that not only do the images go out of focus, they also become distorted, and the magnification changes. As the voltage ratio drops, the image becomes barrel distorted, the magnification increases, and the image intensity decreases. As the voltage ratio increases, the image becomes pin-cushion distorted, the magnification decreases at the center and increases at the periphery, and the intensity at the center increases. The image corresponding to the next-to-highest voltage ratio shows a black ring between an intense central spot and a bright periphery. The ring represents the part of the beam which was blocked by an aperture stop placed in the beam, to discriminate against out-of-focus beams. Because of spherical aberration, the stop was not very effective. In the image recorded at the highest voltage ratio, the outer part of the beam is



3.6 3.23 3.14

3.04 2.94 2.85

2.77 2.69 2.61

Fig. 3. Images of a 2000 lines/in. mesh in focus ($V_C/V_I = 2.94$) and at voltage ratios above and below this setting.

completely blocked and only the intense center remains. This bright spot could, by itself, mask the central part of the in-focus image, if superimposed on it. In this series, the beam current was the same for each image. But even if the in-focus region were favored with a higher current, it seems clear that the high-energy end of the distribution would be disproportionately troublesome, if a telescope were to be used to image a beam with a broad range of energies. The conclusion we drew from this experiment is that some method of narrowing the range of energies which the telescope has to cope with is needed.

Several techniques for dealing with a range of energies in electron beams have been developed for electron microscopy. Energy losses due to the inelastic scattering of electrons passing through the specimen broaden the energy distribution beyond the narrow-energy range in the illuminating beam. The various approaches to solving the problems posed by broad energy beams are discussed by Egerton [5]. The techniques developed for this purpose are used both to improve the resolution by restricting the range of energies to be focused, and for analysis of the energy distribution itself. The devices used include the magnetic prism-mirror energy filter, the omega filter, the Wien filter, and the Gatan imaging filter (GIF). Could these or other devices used in electron microscopy be adapted for use with CP telescopes? An additional consideration in connection with CP beams in space is that attention must be paid to extraneous radiation such as very high-energy particles (charged or uncharged) and photons, which can enter the imaging system, and which are affected little or not at all by prisms and lenses. An in-line optical system would need to have a way of blocking, or otherwise avoiding, these rays. The GIF system is a post-imaging add-on magnetic spectrometer with a 45° bend which can produce energy-selected images. It seems that with such a system the unwanted extraneous radiation could pass through the telescope without interference.

Another method for avoiding extraneous radiation (the method with which we are most familiar [6]) is to deflect the beam which we wish to image away from the initial axis and allow the unwanted radiation to bypass the rest of the optical system. This separation is accomplished by using a magnetic deflector, located at the objective image plane, to bend the beam away from the axis and also to spread it into a spectrum of angles. The beam then passes through a triplet lens combination, which transfers the objective image to a second magnetic deflector (without change of magnification or orientation). The second deflector reverses the bend produced by the first deflector, leaving the beam traveling along an axis which is parallel to, but displaced from, the initial axis. An energy-selecting slit at the entrance to the transfer system limits the energy range to be focused. The fact that deflections take place at image planes, along with the symmetry of the transfer system, largely protects the resolution from the effects of deflection aberrations. The remaining imaging is done along the second axis, with an additional lens to relay the image in the second magnet to the eyepiece.

3. Conclusion

We have shown that there are compelling incentives to use charged particles to image astronomical objects. We have demonstrated that with current technical capabilities, it is eminently possible to image CPs, although it still needs to be confirmed that CPs from space can carry an image. Using just electromagnetic radiation, we can capture a snapshot of the past. However, using CPs in conjunction with traditional electromagnetic radiation, we hope to track the history of stars, galaxies, supernovae, and other astronomical objects. Therefore, we assert that developing a CPT would be an exciting project and could provide a significant scientific return.

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