From Galaxies to Nanocrystals: A Brief Trip Across 30 Orders of Magnitude

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Introduction

As electron microscopists, many of us become engrossed in observing the shape, size, and atomic structure of nanoparticles every day. With our focus on the atoms in a single quantum dot, it is easy to lose sight of the broader physical perspective. This short essay highlights some wider connections as a way of linking electron microscopy to the quest for knowledge on other length scales. The scientific enterprise relies on images that expand the range of human vision, from the galactic to the atomic, from the origins of the universe to the discovery of new materials. From this viewpoint, it is interesting to look at some connections across nearly 30 orders of magnitude.

The Origin of Metals

If you ask students in a class on materials science "where does iron come from?" the unanimous response would be: from a mine, of course. But if you ask "how did the iron get into the mine?" there will be puzzlement. Ask the same question in a class on astrophysics, and the answer is clear: metals come from the stars.

Surprisingly, this was perfectly apparent to the ancient Greeks. In Greek, the word for iron is *sidéron*. Sideral also means *stellar*, or *astral*, as found in the word *asterisk*, simply a stylized star. In the *Odyssey*, Homer evokes a sky made of iron, and the Greeks in the Bronze Age and the Iron Age thought the sky was metallic, born from the Earth. Clearly, the Greeks saw a strong physical connection between the Earth and the sky, and for them this link was of a metallic nature. In this view, Earth's metals were linked directly to the sky, outer space, and the stars. This conviction probably originated, and was surely enforced, by the use of iron meteorites falling from the sky as a raw material for the earliest iron tools and weapons.

Materials are everywhere in our life. Materials science is a living discipline, sustained by the development of innovative fabrication processes and new characterization techniques that let us make and observe materials literally one atom at a time.

Observation and the Star Power of Metals

It is the passion for observation that makes us stare through the binocular of an electron microscope during the day and the eyepiece of a telescope at night. Figure 1 below illustrates what we can see at the two scales. The telescope image shows the Whirlpool Galaxy M51 in the constellation *Canes Venatici* (the Hunting Dogs), while the microscope image shows the atomic structure of a cadmium selenide nanocrystal, in the form of a quantum dot. The front spiral galaxy in M51 spans 100,000 light-years (~10^{21} m), which is a typical size for spiral galaxies, such as our Milky Way. Quantum dots are fluorescent semiconductor nanoparticles that emit light whose wavelength depends on the size of the particle due to quantum confinement of the Bohr exciton; the smaller the quantum dot, the more the fluorescence is shifted toward blue. Thus on the nanoscale, for many

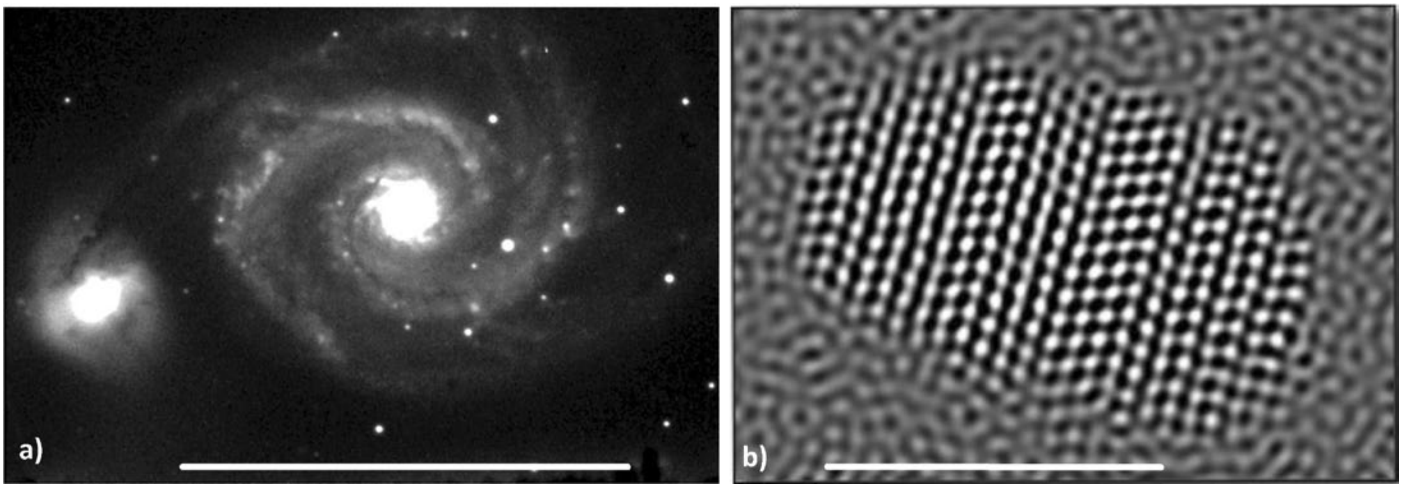

Figure 1: a) Messier object M51, the "Whirlpool Galaxy" in Canes Venatici, near the Big Dipper. Image taken with the 600 mm Newtonian Cassegrain TJMS telescope of the Buthiers Observatory, France (A. Thorel and J. Rodriguez, scale-bar = 100,000 light-years). b) Atomic structure of a cadmium-selenide quantum dot (courtesy B. Dubertrert). Image taken with the Tecnai F20ST microscope at the Materials Centre of Mines-ParisTech (A. Thorel, scale-bar = 5 nm).

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nanoparticles, color is directly related to size. The size of a quantum dot is typically 5 nm ($5 \cdot 10^{-9}$ m); therefore the ratio between the size of a galaxy and that of a quantum dot is about $2 \cdot 10^{29}$, which is almost 30 orders of magnitude!

The cadmium and selenium atoms that make up the quantum dot were created in a supernova explosion of a massive star reaching the end of its life. Stars form in the spiral arms of galaxies, like that shown in Figure 1a. The star maintains a balance between gravity, which tends to make it collapse, and thermonuclear reactions, which counteract the collapse. During its lifetime, the star produces increasingly heavy chemical elements by successive thermonuclear fusion reactions of lighter elements, from helium up to iron through a process called nucleosynthesis. The sequence of these steps is controlled by the initial mass of the star. Iron is the most stable element at the nuclear level. Elements heavier than iron are produced in the explosion of more massive stars, more than eight times the mass of the sun.

It is fascinating to note that our everyday materials come from the stars, through nucleosynthesis or supernovae. Humans are stardust—literally—because the chemical composition of the human body is much closer to the stars than to Earth, and the iron in our blood was produced by a star collapsing somewhere in the universe.

Beyond this chemical connection, it is intriguing that the physical laws controlling the behavior of a quantum dot are identical to those governing the M51 galaxy. It appears that the four primary forces (gravity, electromagnetic force, strong nuclear interactions, and weak nuclear interactions) are valid from the cosmological to the atomic scale.

Heisenberg tells us that if a particle is confined to an increasingly smaller volume, its speed, and hence its energy, will increase. In extreme conditions, such as those that can be encountered in white dwarfs for example, the gravitational pressure is so strong that the electrons are confined in a volume approaching h^3, which is the smallest volume that can be occupied by one electron, with one or the other of its two possible spins. In this volume, it is impossible to fit another electron in the same quantum state, eventually leading to the so-called degeneracy pressure. When the star has a greater mass (more than 8 solar masses), this pressure is overcome and electrons and protons merge, leading to a neutron star that expels its outer layers via an elastic rebound called a supernova. For an even greater mass (25 solar masses), the degeneracy pressure applied this time to neutrons is overcome in a singularity known as a black hole. Via successive catastrophic spurts, this stellar evolution releases elements by nucleosynthesis, including cadmium and selenium, the basic components of our quantum dot.

The loop is closed, revealing a degree of kinship even closer than initially apparent. These two vastly different objects, collapsing stars and luminescent nanoparticles, behave the way they do because they are subject to the same rules of quantum confinement.

Images and Materials Science

At both extremes of the research enterprise, astrophysics and materials science, we follow our curiosity to arrive at an understanding based on observation. Images have always been essential to man, to help comprehend and interpret our world. The eye, a remarkable feat of evolution, is the most appropriate and delicately-tuned tool to capture images at the human scale. However, our desire to explore the world beyond the limits of our eyes led us to develop new tools to see the invisible, from the microscopic to the astronomical. The farther we want to push the boundaries of observation, the more sophisticated and expensive the instruments needed. It is striking that the invention and use of optical devices for looking at far objects (telescope, from the Greek *teleskopos*, "seeing far") and looking at small objects (microscope, from the Greek *microskopos*, "seeing small") started exactly at the same time at the onset of the XVIIth century with Galileo Galilei (1564–1642), who participated in the invention and improvement of both instruments.

Thanks to the invention of photography by Nicephore Nièpce and his brother Claude [1, 2] images have become objects. It took a long time before this invention was coupled to microscopes and telescopes. Until not so long ago, a researcher would draw on a sheet of paper the cells or microbes observed in a microscope or the equatorial bands of the planet Jupiter viewed through a telescope. First recorded on glass plates, then on polymer films, and now on CCD sensors, images are an essential part of the process of knowledge acquisition. They are as important for the study of materials as they are for understanding the universe.

Materials science is largely based on observation: we look inside the material to understand its properties and to appreciate the natural beauty of the observed microstructures. Since its invention by Ernst Ruska, the electron microscope has contributed to remarkable advances in the fields of mechanics, electronics, optics, ferroelectricity, magnetism, etc. This instrument led to the development of materials that have revolutionized technology and manufacturing. To understand a material we need to learn about its microstructure. That is why more than half of all research papers in materials science over the last several decades contain results from electron microscopy.

Materials and Instrumentation: Correlated Evolutions

From the Stone Age to the Industrial Revolution, the fate of humanity has been linked to materials. Tools made from stone, bronze, iron, or silicon define eras in the development of civilization [3]. Many recent advances in technology, such as fiber optics, lasers, and superconductors, were made possible by advances in materials. The accelerating pace of materials discovery and design has fueled a demand for more sophisticated characterization tools, such as electron microscopes with ever greater resolution. Conversely, electron microscopy itself has become a tool for discovery of materials. Nanotubes, fullerenes, and quasicrystals, new forms of matter with remarkable potential for technological innovation, were discovered with the aid of electron microscopy.

Innovations in materials and in techniques for characterization are synergistic. Advances in materials require new tools for observation, and sophisticated microscopes provide better knowledge of materials. Advances are made by an interplay between the measurement of properties, the observation of the microstructure, and a model that connects the two.

In his famous 1959 lecture entitled “There is plenty of room at the bottom,” Richard Feynman dreamed of building materials atom by atom and observing them with atomic resolution images [4]. Since then, materials synthesis and instrumentation have developed at a rate that would have been hard to imagine even a couple of decades ago.

Extraordinary new materials have emerged—sometimes almost by accident (for example, high-Tc superconductors, nanotubes, or quasicrystals) and sometimes through a long process of incremental research (for example, superalloys or composites). At the same time, great advances have been made in instrumentation. Thanks to the revolution in aberration correction, electron microscopy is now able to provide sub-Ångstrom resolution and sub-eV electron spectrometry [5, 6]. Our vision of materials has become quantitative, analytical, and three-dimensional. Atomic-resolution tomography, spectrum imaging, and time-resolved observation of atomic mechanisms and dynamics are coming within reach. Within the next decade, it may become possible to observe the diffusional motion of individual atoms, the path of diffusionless transformations, the mechanisms of phase transformations, or the route of chemical reactions at atomic resolution. Electron microscopy has become an indispensable tool of exploration in the pursuit of knowledge at one end of a scale that spans 30 orders of magnitude.

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