
Now is the time, the walrus said, to talk of many things…
—Lewis Carroll, “The Walrus and the Carpenter”

In the previous chapter we outlined the story of how galaxies have likely assembled into the forms we see in the modern universe. This formation is largely based on observational properties of these systems that allow us to construct how these galaxies were put together.

However, astronomers are interested in much more than the way galaxies assemble and form. The problem of galaxy assembly ultimately ties in with some very deep physics, including the existence and type of dark matter contained in these systems, as well as to the existence of black holes. The last few decades have seen an explosion in our understanding of the internal physics of galaxies as well as learning how they form.

Galaxies it turns out are not simple systems in the way that, say, stars are. The formation histories of galaxies covers over 13 billion years, and involves around at least a dozen different processes that happen at various times over the course of the history of a galaxy, and many of these are still going on today. In some ways it makes as much sense to ask when and how a galaxy forms as it is to ask when and how large cities such as London or New York assembled.

However, there are major clues to how the process has occurred, and we can identify some of the major aspects, detailed in the last chapter. However it is possible, if not likely, that there are still galaxy formation processes we have not yet identified.

One of these is that galaxies do not form in a random way, but follow the structure of the universe, and their assembly is largely determined in a bulk way on the properties of the universe. One of the major ways this is done is through the dark matter, which provides the structure or scaffolding in which galaxy assembly takes place.
In fact, it has become clear in the last few decades that the vast majority, up to 90% or more, of the mass in a galaxy is in a dark form, whose nature is unknown, but whose gravitational force can profoundly influence the way that galaxy formation has occurred.

**Dark Matter Takes the Stage**

Hints for the existence of dark matter in galaxies have been around almost as long as we have known about galaxies. Historically, the first clue that there was something else within the universe beyond the stars, dust, and light that can be detected directly originated from measurements of the motions of, and within, galaxies.

**Shots in the Dark**

The first time astronomers found something amiss in the observations of galaxies that suggested there was a dark component to galaxies was in 1933. In that year, the astronomer Fritz Zwicky, in one of his first observational astronomy papers, took deep spectra of galaxies in the Coma cluster to measure the motions of individual galaxies.

Zwicky came relatively late to astronomy and had started his research career as a physicist. Born in Bulgaria in 1898 to a Swiss father, he attended the Eidgenossische Technische Hochschule (ETH) in Zurich, the same institution where Einstein was a student two decades earlier, completing his diploma thesis (first degree) under mathematician Hermann Weyl and his Ph.D. dissertation in the theory of crystals under future Nobel laureate Peter Debye. In 1925 he moved to Caltech at the invitation of its president Robert Millikan (earlier, Millikan had been one of the young Edwin Hubble's teachers at the University of Chicago, and had won the Nobel prize in physics two years earlier for his measurement of the charge on the electron by studying the behavior of oil droplets in electrical fields). Though Zwicky spent nearly his entire career in the United States, he remained a Swiss citizen, once remarking that “a naturalized citizen is always a second-class citizen.”

Though Millikan had expected Zwicky to work on the quantum theory of solids and liquids, which was closer to his dissertation topic, Zwicky already showed his independent streak, and though he did some work along the lines expected, his interests gradually turned to astrophysics. At first he was interested in trying to understand the origin of cosmic rays—high-energy protons and atomic nuclei coming from outside the Solar System. Then, after Hubble published his 1929 paper on the velocity-