

“ACHARIT HAYAMIM”: THE FUTURE OF OUR UNIVERSE

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Previous generations of scholars have wondered occasionally about the long-term future, or in biblical terms: the forecast for “acharit ha'yamim”. For the first time in history, we now have a “standard cosmological model” which agrees with a large body of data about the past history of the Universe to an unprecedented precision. This model makes scientific predictions for the future. Below I summarize those predictions for the simplest version of the standard cosmological model (with a steady cosmological constant).

In fact, every time an American president delivers the “State of the Union” address I imagine what it would be like to hear a supplementary comment about the “State of the Universe” that surrounds the “Union”. It is completely natural for the president to focus on issues which affect re-election on a four year timescale and to ignore cosmological events that take billions of years. But I nevertheless find it amusing to imagine a brief statement about the bigger picture, especially when we gain a significantly better understanding of our future in the cosmos than previous generations of astronomers had. And since cosmologists reached a major milestone of this quality over the past decade, let us consider below what our new understanding of the Universe might entail for our future.

Cosmologists can actually *observe* how the Universe looked like in the past due to the finite speed of light. The light that we observe today from a distant source must have been emitted at an earlier time in order for it to reach us today. Hence by looking deeper into the Universe we can see how it looked like at earlier times. The situation is analogous to an archeological dig. And if we are able to measure distances, we can also infer how the expansion rate of the Universe evolved with cosmic time. Naively one would expect the expansion to have slowed down with time because of the gravitational attraction of the cosmic matter. *But could this expectation be tested by observations through telescopes?*

A simple way to infer the distance of a street light with a 100 Watt bulb is to measure how bright it appears at night. The 100 Watts it produces are being spread over a spherical surface area that increases in proportion to the square of the distance. Therefore, the observed flux of radiation (namely the radiation energy per unit time per unit area) will dilute as the distance squared and this can be used to calculate the distance. Fortunately, exploding stars of a particular type (the so-called *Type Ia supernovae*) provide a standardized “light bulb” that can be seen out to the edge of the Universe. Over the past decade, two groups of observers inferred distances to a large number of supernovae. Contrary to naïve expectation, they discovered that the cosmic expansion had been speeding up (i.e. *accelerating*) over the past five billion years. Einstein's theory of gravity allows for an accelerating Universe if the mass density of the vacuum is bigger than half that of matter (which naturally occurs at late times as matter gets diluted by the

cosmic expansion but the vacuum remains constant). An unchanging vacuum, which would make the so-called *cosmological constant*, naturally produces “repulsive” gravity that would push galaxies away from each other at an ever increasing rate. With this discovery in mind, what should the president say about the “state of our Universe”?

To put it bluntly: **the state of our Universe is not looking good for future observers**. If the Universe is indeed dominated by a cosmological constant and if the corresponding vacuum density will remain constant as the Universe ages by another factor of ten, then all galaxies outside our immediate vicinity will be pushed out of our horizon by the accelerated expansion of space (see Figure 1). In a short paper I have published in 2002, entitled “The Long-Term Future of Extragalactic Astronomy”, I showed that in fact all galaxies beyond some distance (a redshift of $z = 1.8$) are already outside our horizon right now (see Figure 2). The light that we receive from them at this time was emitted a long while ago and does not represent their current state. If this light encodes some message from a distant civilization, then any reply we send back will be lost in space and never reach its target. Within a finite time, the accelerated expansion of space moves any distant galaxy away from us at a speed that exceeds the speed of light. Even light (which represents the fastest speed by which material particles can propagate) is ultimately unable to bridge across the inflating gap that is opened between distant galaxies and us by the accelerated cosmic expansion.

The situation is similar to observing a friend cross the event horizon of a black hole. From a distance, we would see the image our adventurous friend heading towards a black hole, getting fainter, and eventually freezing at some final snapshot, as that friend appears to be hovering just above the horizon. The frozen image will represent the snapshot of the friend as he crosses the horizon in his rest frame. Beyond that point in time, no information can be retrieved about the whereabouts of the friend in classical general relativity.¹

Since the image of each galaxy will eventually freeze at some finite time in its rest frame, there is a limited amount of information that we can collect about each distant galaxy. In particular, we will never be able to study the evolution of a galaxy beyond some finite age in its own frame of reference. The more distant a galaxy is, the earlier its image will freeze and the less information will be available to us about the way it ages.

Of course, bound systems which are held together by a force that is stronger than the repulsive force of the cosmological constant, do not participate in the cosmic expansion. This includes electrons bound to atoms by the electromagnetic force, planets bound to the sun as well as galaxies bound together by a stronger gravitational pull than the cosmic repulsion.

Which galaxies will remain bound to us and which will fly away? To figure this out, we ran with Ken Nagamine in 2003 a computer simulation of the future evolution of

¹ My paper from 2002 on the subject entitled: "Long Term Future of Extragalactic Astronomy" was mistaken by some to be dealing with funding priorities for NSF and NASA. The concluding paragraph of this article suggests that this was not necessarily a mis-interpretation of my paper.

all galaxies within a hundred million light years of the Milky Way (see Figures 3 and 4). Our simulation used a realization of the local distribution of galaxies based on existing observational data. The simulation indicated that all galaxies outside the local group of galaxies within a distance of 3 million light years, are not bound to us and will be pushed out of our view by the cosmic expansion. The gas in between galaxies will get extremely cold but remain mostly ionized as it is today (see Figure 5).

How will the local group of galaxies look like in the distant future? The two major constituents of the local group of galaxies, namely our own Milky Way galaxy and its nearest neighbor, the Andromeda galaxy (Figure 6), are on a collision course. The Doppler shift of spectral lines from Andromeda indicates that Andromeda and the Milky Way are moving towards each other radially at about a hundred kilometer per second, but provides no information on the transverse speed. Indirect arguments suggests that the transverse speed is modest and the two galaxies are bound. Future observations will pin down the transverse speed better, but bearing the uncertainties in mind we have recently performed with TJ Cox a numerical simulation of the collision between the two galaxies.

For the most likely parameters of the local group, the merger of the Milky Way and Andromeda will likely take place within a few billion years (see Figure 7). Since the lifetime of the sun is longer, this event will potentially be visible to observers in the solar system. With TJ Cox, we have recently simulated this future merger event and examined what will happen to the sun in the process (see Figure 8). We find that the sun will be kicked out to a distance that is a few times larger than its current separation from the center of the Milky Way. During the merger, the Milky Way might appear as an external galaxy to solar system observers. Also the night sky will change. Currently the thin disk of the Milky-Way in which we reside, appears as a strip of stars on the sky. These stars will be scattered by the merger into a more spherical distribution, resembling a spheroid. The merger product of the collision between the Milky Way and Andromeda will make a new galaxy, which I termed “Milkomeda”.² The spheroidal shape of Milkomeda is not unusual, as it characterizes a major class of galaxies called “elliptical galaxies”. Presumably, many of these galaxies in the present-day Universe formed out of mergers between galactic disks at earlier cosmic times. Ultimately, only Milkomeda will remain visible to future solar system astronomers.

It is then interesting to ask the following hypothetical question. Suppose all scientific archives will be lost by some cataclysmic event. In that case, *will archeology of Milkomeda by future astronomers be able to reveal that it originated from the big bang as compared to an alternative hypothesis of an island galaxy that was embedded in vacuum for a long time?*

The current state of an accelerating Universe makes the study of cosmology a transient episode in our long-term scientific endeavor. We better observe the Universe in the next tens of billions of years and document our findings for the benefit of future scientists who will not be able to do so. It would seem prudent for funding agencies to allocate their funds for cosmological observations over the next tens of billions of years,

² This is the first paper in my publication record that has a chance of being cited in a few billion years.

before studies of this sort will be impossible. Once cosmological observations become pointless, the funds could be taken away from this line of research and be dedicated instead to solving our local political problems. At that time, the presidential State of the Union address will be fully justified in ignoring the (empty) state of our Universe at large.

Biographical Sketch

Abraham Loeb is Professor of Astronomy at Harvard University, a visiting professor at the Weizmann Institute of Science, and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He is a world leader in theoretical cosmology.

Related Scientific Papers by the Author

- Loeb, A. “The Long-Term Future of Extragalactic Astronomy”, *Phys. Rev. D* **65**, 047301, 2002. See <http://arxiv.org/abs/astro-ph/0107568>
- Nagamine, K., & Loeb, A., “Future Evolution of Nearby Large Scale Structure in a Universe Dominated by a Cosmological Constant”, *New Astronomy*, **8**, 439, 2002. See <http://arxiv.org/abs/astro-ph/0204249>
- Nagamine, K., & Loeb, A. “Future Evolution of the Intergalactic Medium in a Universe Dominated by a Cosmological Constant”, *New Astronomy*, **9**, 573, 2004. See <http://arxiv.org/abs/astro-ph/0310505>
- Cox, T. J., & Loeb, A., “The Collision Between the Milky-Way and Andromeda Galaxies”, *MNRAS*, submitted, 2007. [arXiv:0705.1170]. See <http://www.cfa.harvard.edu/~tcox/localgroup/>

Photons in an Accelerating Universe are Analogous to Ants on an Inflating Balloon

Ants = Photons

Balloon=Expanding Space

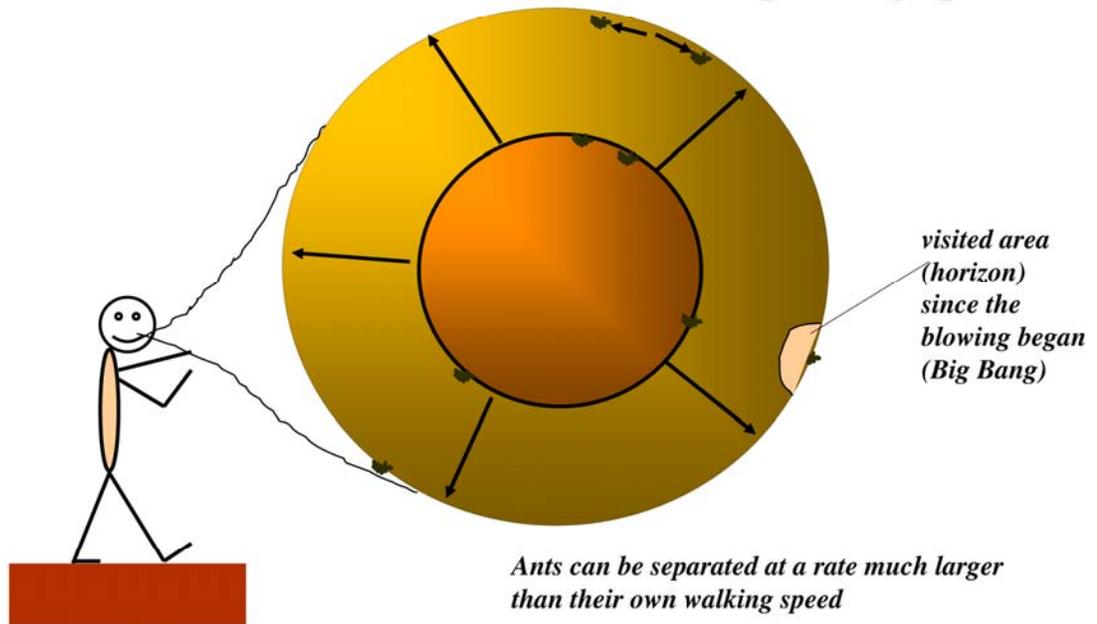
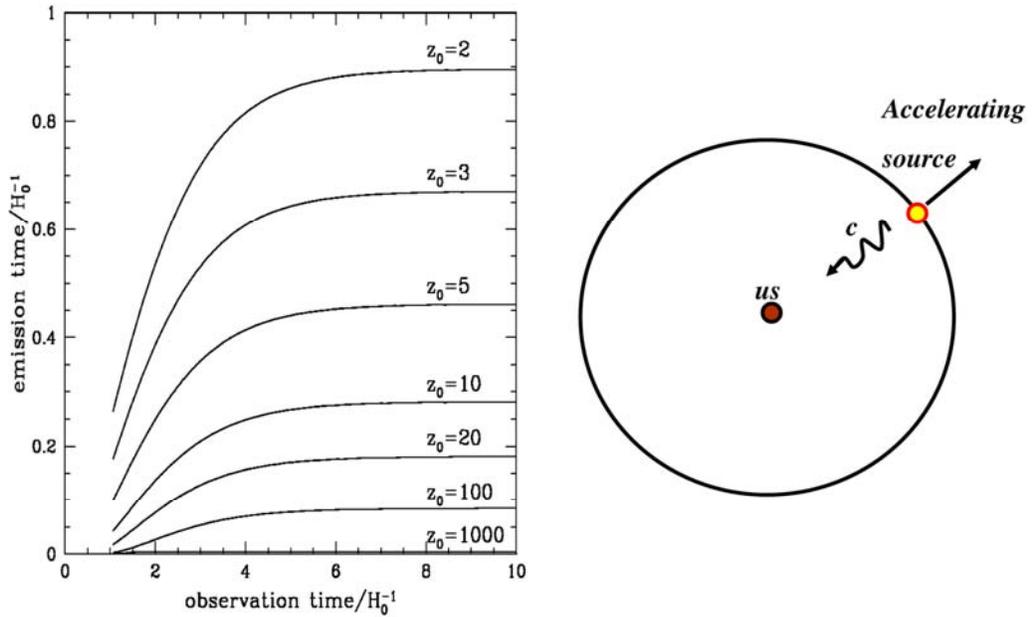


Fig. 1.— The propagation of photons in an accelerating Universe is similar to the motion of ants on the surface of an inflating balloon. If the balloon is inflated at a rate that increases with time, the ants will be able to visit only a very limited region on the balloon surface. Similarly, photons will be able to go across a limited region of the Universe if space itself is inflating at an accelerated rate.

The Long Term Future of Extragalactic Astronomy



All galaxies beyond a redshift of $z=1.8$ are already outside our horizon (no cell phone communication to $z>1.8$!). (Loeb 2001)

Fig. 2.— The accelerated cosmic expansion of space pulls distant galaxies away from us at a speed that increases with time. When the speed of a galaxy relative to us exceeds the speed of light, the image of that galaxy would freeze and fade away. No additional information can be gathered on the subsequent history of that galaxy, and no subsequent communication is possible with its inhabitants. The plot on the left shows the the time at which light is emitted by a distant galaxy as a function of the (future) time at which it is observed (from Loeb 2001). Time is measured in units of $t_H = H_0^{-1} = 14 \text{ Gyr}$, and the current cosmic time is $t_0 = 0.96 H_0^{-1}$, where H_0 is the present-day Hubble constant. For any currently measured redshift z_0 of a source, there is a maximum intrinsic age up to which we can see that source even if we continue to monitor it indefinitely.

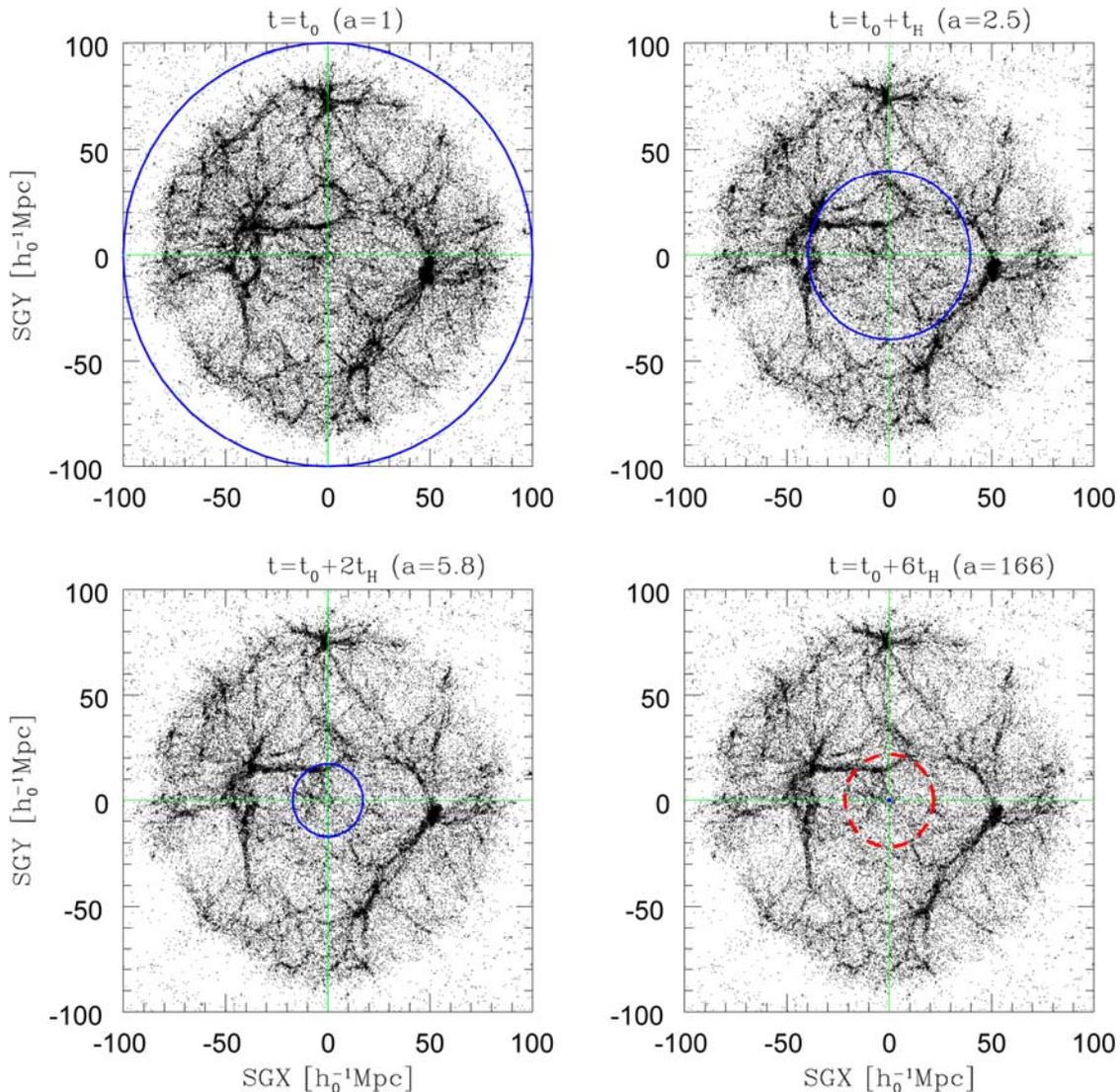


Fig. 3.— Future evolution of the distribution of galaxies in the vicinity of the Milky Way galaxy (from Nagamine & Loeb 2003). The cosmic expansion was taken out from this visualization by using coordinates that expand together with the Universe (the so-called, *comoving coordinates*). Shown are galaxies in a slab of a thickness of $30 h^{-1}\text{Mpc}$ projected onto the supergalactic XY plane at the times $t = t_0$, $t_0 + t_H$, $t_0 + 2t_H$, and $t_0 + 6t_H$ where t_0 is the present time and $t_H = 14(h/0.7)^{-1}\text{Gyr}$ (corresponding to a cosmic scale factor $a = 1.0, 2.5, 5.8,$ and 166) from top left to bottom right. Here h is the present-day Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The thick solid circle in each panel indicates the physical radius of $100h^{-1}\text{Mpc}$ around the supergalactic center. In the bottom right panel, the Universe has expanded so much that this circle is no longer visible. Instead, we show the event horizon at a physical radius of $3.6h^{-1} \text{ Gpc}$ as the thick dashed circle.

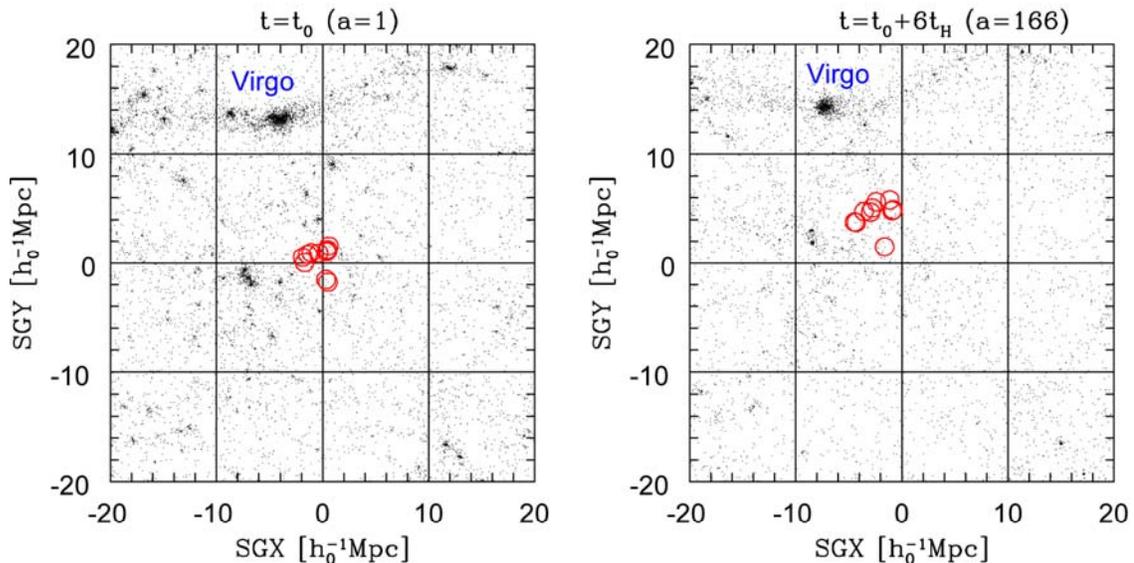


Fig. 4.— Similar to Figure 3 but zooming on the immediate neighborhood of the Milky-Way galaxy and the Virgo cluster of galaxies in which it resides (from Nagamine & Loeb 2003). Shown is the galaxy distribution in a slab of a thickness of $30h^{-1}$ Mpc projected onto the supergalactic XY plane. The left panel shows the projection today, and the right panel shows it at $t = t_0 + 6t_H$. The Virgo cluster appears near the top of the image. Open circles mark particles that are within a radius of $2h^{-1}$ Mpc from the supergalactic center at the present time. They advance towards Virgo by a comoving distance of $\sim 5h^{-1}$ Mpc, but do not fall into it at late times. Most of this displacement is completed by $t = t_0 + 2t_H$. To get the actual physical distance to Virgo in the future, the final (constant) separation in comoving coordinates should be multiplied by an inflating factor that grows exponentially with cosmic time. This implies that in real space the Milky Way is not bound to the Virgo cluster and all galaxies outside the Local Group (which includes only the Milky Way and its nearest massive neighbor, Andromeda) will exit from our visible horizon in the future.

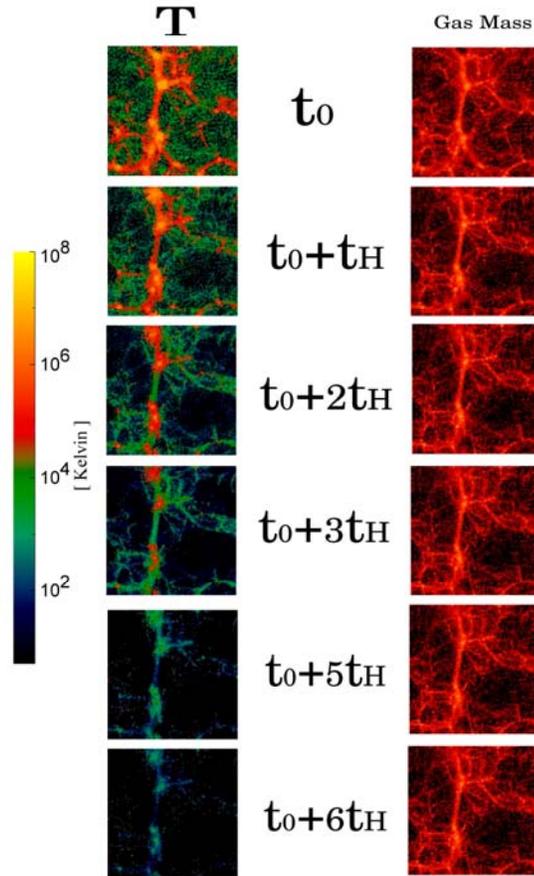


Fig. 5.— Numerical simulation of the future evolution of the cosmic gas in the accelerating Universe depicted in Fig. 3 (from Nagamine & Loeb 2004). Shown is the projected distribution of mass-weighted gas temperature, T , in K (left column) and projected gas mass (right column) for a simulation slice with a comoving thickness of $10h^{-1}\text{Mpc}$ and a comoving width of $50h^{-1}\text{Mpc}$ on a side. In the future, the intergalactic gas will get rarefied and cool to extremely low temperatures but will remain ionized (because of its low density).



Fig. 6.— Four images of the nearest big galaxy, Andromeda, which is headed on a collision course with the Milky-Way galaxy (source: R. Guhathakurtha, UCSC). The two galaxies will fly very close to each other within a few billion years, and eventually merge into a single galaxy within 5 billion years, before the sun will die. During their first close encounter within, Andromeda will appear as big on the sky as the Milky Way.

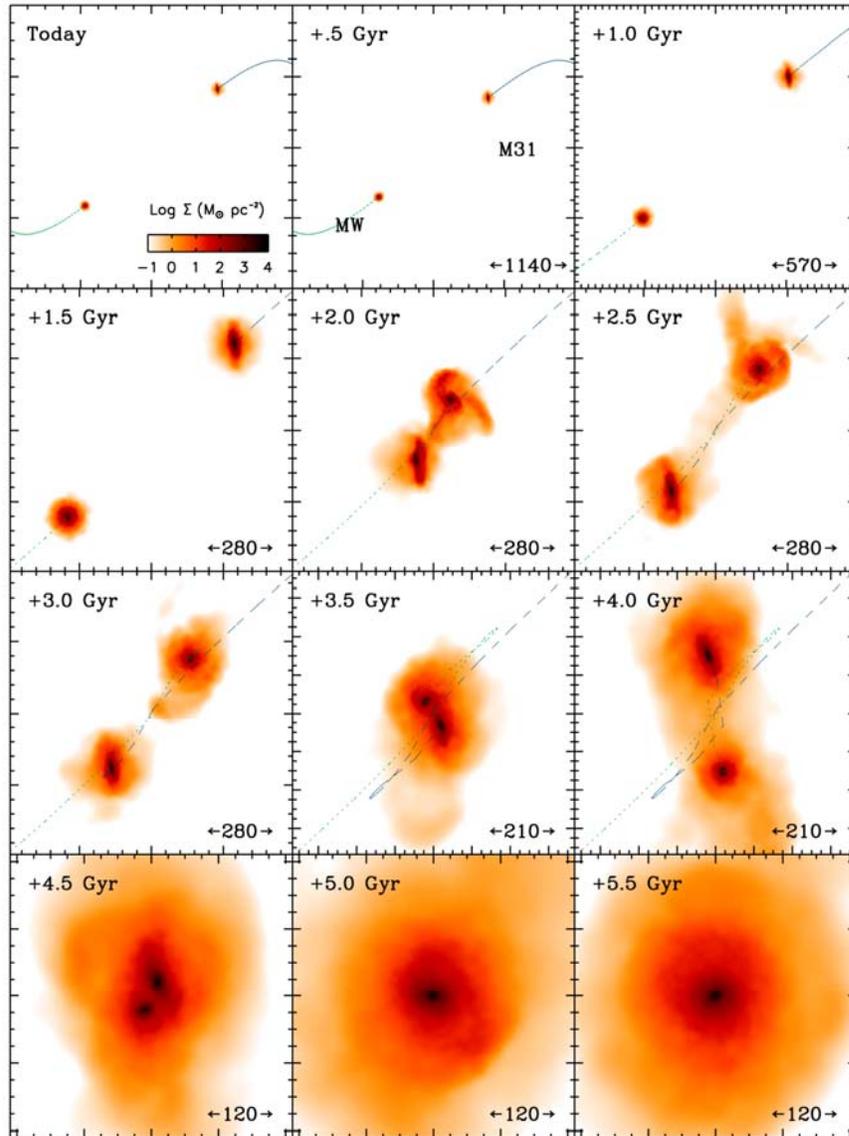


Fig. 7.— The merger product of the Milky-Way (MW) and its nearest neighbor - the Andromeda (M31) galaxy, will be the only object visible to us in the night sky once the Universe will age by another factor of ten. The set of images show the forecast for the evolution of this future collision based on a state-of-the-art computer simulation (from Cox & Loeb 2007). Shown through the red scale is the time sequence of the projected density of stars. Andromeda is the larger of the two galaxies and begins the simulation in the upper-right. The Milky Way begins on the edge of the image in the lower-left. Panels have varying spatial scales as specified by the label, in kpc, on the lower-right of each panel. The simulation time, in Gyr relative to today, appear on the top-left label of each panel. The trajectories of the Milky Way and Andromeda are depicted by the blue solid lines.

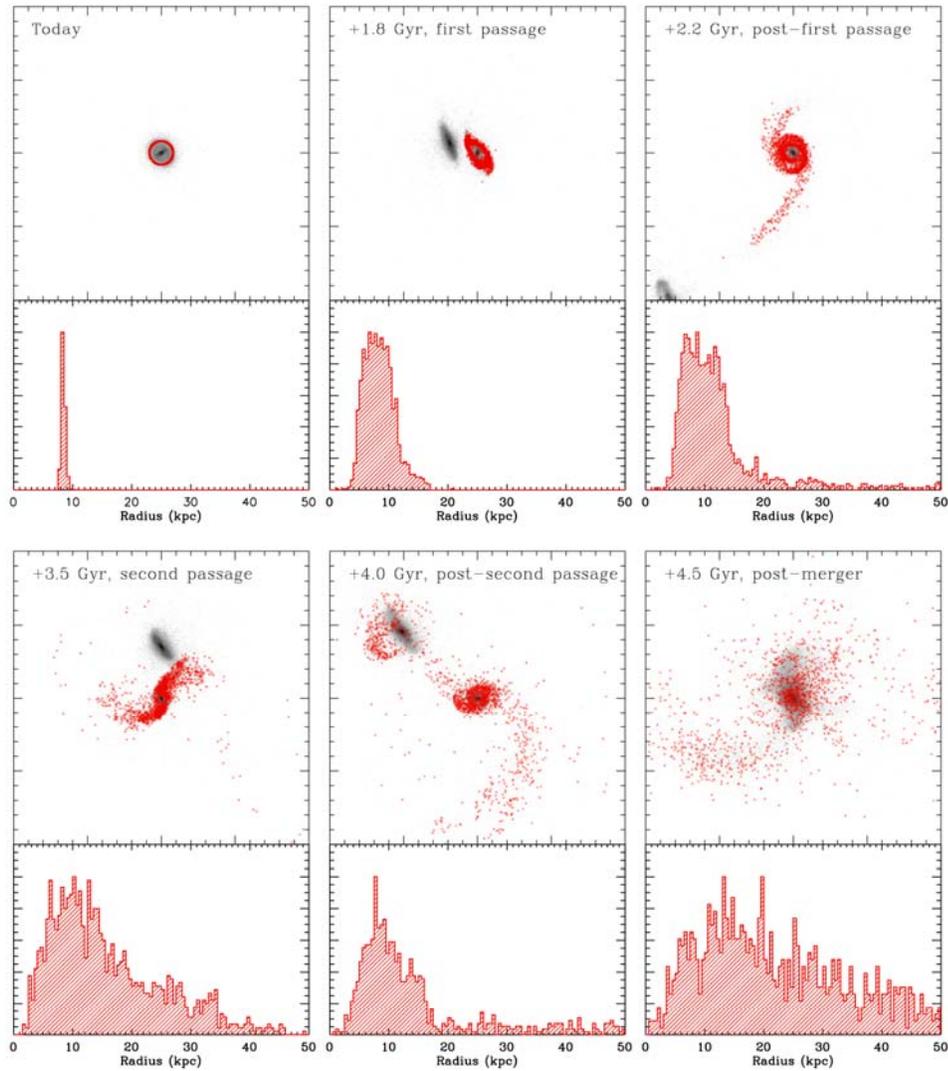


Fig. 8.— The possible location of the Sun during various stages of the merger between the Milky Way and Andromeda (from Cox & Loeb 2007). The top panel shows all stellar particles in our simulation that have a present-day galactocentric radius of 8 ± 0.1 kpc with a red cross and tracks their position into the future. The bottom panel presents a histogram of the radial distance from the center of the Milky Way.