Fermi's paradox, extraterrestrial life and the future of humanity: a Bayesian analysis

Vilhelm Verendel [*]

Department of Energy and Environment, Chalmers University of Technology, 412 96, Gothenburg, Sweden

Olle Häggström [†]

Department of Mathematics, Chalmers University of Technology, 412 96, Gothenburg, Sweden

November 19, 2015

---

[*]Corresponding author. Electronic address: `vive@chalmers.se`; Adress: Physical Resource Theory, Department of Energy and Environment, Chalmers University of Technology, 412 96, Gothenburg, Sweden. Telephone: +46 31 772 3107. Fax: N/A.

[†]Electronic address: `olleh@chalmers.se`

Abstract

The Great Filter interpretation of Fermi's great silence asserts that Npq is not a very large number, where N is the number of potentially life-supporting planets in the observable universe, p is the probability that a randomly chosen such planet develops intelligent life to the level of present-day human civilization, and q is the conditional probability that it then goes on to develop a technological supercivilization visible all over the observable universe. Evidence suggests that N is huge, which implies that pq is very small. Hanson (1998) and Bostrom (2008) have argued that the discovery of extraterrestrial life would point towards p not being small and therefore a very small q, which can be seen as bad news for humanity's prospects of colonizing the universe. Here we investigate whether a Bayesian analysis supports their argument, and the answer turns out to depend critically on the choice of prior distribution.

1 Introduction

Recent discoveries such as Earth-like planets in the habitable zone around another star (Quintana et al. 2014, Cassan et al. 2012) could plausibly increase expectations to find life elsewhere and possibly under similar conditions as on planet Earth. However, in contrast to popular opinion, Hanson (1998) and Bostrom (2008) have suggested that a future discovery of extraterrestrial life would be bad news for humanity. The reasoning behind this view rests on Hanson's so-called Great Filter formalism (Aldous 2012, Hanson 1998). The number N of potentially life-supporting planets is huge (perhaps around 10^{22}) (Cassan et al. 2012). Take p to be the probability that a randomly chosen such planet develops life and a technological civilization on the level of humanity today, and q to be the probability that a randomly chosen planet having reached that level goes on to form a super-technological civilization, defined as one that is noticeable to astronomers everywhere in the observable universe. Then the expected number of such super-technological civilizations is Npq. The great silence of the Fermi Paradox (Webb 2002, Ćirković 2009) indicates that the actual number of such super-technological civilizations is 0, suggesting that the order of magnitude of Npq is at most 1. The fact that there is an astronomical number of exoplanets would imply that pq is very small, but discovery of extraterrestrial life would be evidence that p is not very small, in which case q must be very small, which in turn suggests that humanity's prospects of eventually reaching the maturity of a super-technological civilizations are bleak. In the present paper we investigate whether or not a rigorous statistical analysis supports this.

The issue of what the discovery of extraterrestrial life would mean to humanity has a certain timeless flavor to it. Yet, it is perhaps more pressing now than ever, for two reasons. First, it has become increasingly clear that humanity in the coming century or so faces a number of non-negligible risks threatening our very existence (Bostrom & Cirkovic 2008, Pamlin & Armstrong 2015, Bostrom 2014, Martin 2006, Rees 2003); a very small value of q might be an indication that the situation requires even more care than we have hitherto realized. Second, the discovery of exoplanets,

many of which seem to be potentially life-supporting, is proceeding at a rapid pace (Petigura et al. 2013), and perhaps we will soon attain the ability to detect definite signs of life out there (Brandt & Spiegel 2014).

We write

$$Npq \not\gg 1\,, \tag{1}$$

for the claim that Npq has order of magnitude at most 1. This relation is called the Great Filter, as it says that all or almost all planets are filtered out somewhere on the path from its genesis to the emergence of a super-technological civilization. The Great Filter has a predecessor in the Drake equation for the number of civilizations active in radio astronomy in the Milky Way, which was formulated by Frank Drake in 1961, and which since then has enjoyed an iconic status in the search for extraterrestrial intelligence (Webb 2002). The Great Filter differs from the Drake equation, not only in a choice of factorization that zooms in on the future prospects for present-day humanity, but also in a number of other aspects, including lifting the focus from the Milky Way to the entire visible universe, a move that is motivated by the apparent in-principle feasibility of both intergalactic colonization (over long time scales) and the construction of engineering structures visible over intergalactic distances (Armstrong & Sandberg 2013, Griffith et al. 2015, Häggström 2016). While it is conceivable that there could be very advanced civilizations that are for some reason invisible to us, basic evolutionary arguments and the astronomical time scale of the universe suggest that if advanced technological civilizations were common, some of them would have been observable here long ago (Hart 1975, Hanson 1998, Häggström 2016). Again, this suggest that pq has to be really small.

It seems to us worthwhile to investigate whether the arguments of Hanson (1998) and Bostrom (2008) on the discovery of extraterrestrial life as bad news to humanity survive a more rigorous statistical analysis. In the choice between a frequentist statistical formalism and a Bayesian one, we opt for the latter. A general reason in favor of a Bayesian framwork is that it is the only one that can produce probabilistic statements about the whereabouts of the parameter values of interest. A more spe-

4

cific reason is that the philosophy behind frequentist statistics, with its emphasis on independent repetitions of experiments (Cox & Hinkley 1979, Salsburg 2001), seems ill-suited to the present context, as we observe Fermi's great silence once and for all, so that the idea of independently repeating the experiment borders on the nonsensical. A downside of the Bayesian approach is that (as we shall see) the results may depend on the choice of prior distribution, especially so when data are sparse.

2 Analysis

To accomodate the possibility of observing *primitive* life on another planet, we choose to factorize p in the Great Filter equation (1) one step further as $p = rs$, where r is the probability that a randomly chosen planet with potential for supporting life does develop life to the level of (say) amoebas, and s is the probability that such a planet goes on to the level of persent-day human technological civilization, conditional on having reached the amoeba level. Thus, (1) turns into

$$Nrsq \ggg 1 \,. \tag{2}$$

Note that relations (1) and (2) are neither very precise statements, nor known truths, but should be thought of as plausible conjectures given Fermi's great silence.

For the Bayesian analysis, we think of N as fixed and very large, and need to devise a prior on $[0, 1]^3$ for the three unknown parameters r, s and q. Estimating how likely emergence of life is on a typical planet, as quantified by r and s, is yet a basic unresolved question possibly spanning physics, chemistry and biology (these could also inform us about crucial barriers in q). Given that a Great Filter could also relate to some difficulty of developing social complexity, social sciences may have a relevant role to play as well. Biogenesis suggests that $r > 0$, but it could be very small (and similarly for s). Without more precise knowledge, it makes sense to have a prior that is spread out all over [0,1] for each parameter. A natural first idea is to take the prior to be uniform on $[0, 1]^3$, corresponding to each of the three parameters

being, independently of the others, uniformly distributed on $[0, 1]$.

Our (partly hypothetical) data is as follows. First we have the great silence, which we represent as N independent Bernoulli trials with success probability rsq, all taking value 0 (failure to produce noticeable super-technological civilisations). Then we consider the effect of two different (hypothetical) possible observations. First, to observe amoeba-level primitive life on a single planet, represented as a Bernoulli trial with success probability r taking value 1 (success). Second, to observe a technological civilization on the level of humanity today, a Bernoulli trial with success probability rs. In particular, we are interested in what effect this has on the statistical uncertainty about q.

At this point, we expect that attentive readers will suggest that we have one more piece of data to take into account, namely the observation that on planet Earth, we have evolved – a probability p ($= rs$) event. Following Bostrom (2008), we believe that including that piece of data in the Bayesian conditioning would be a mistake, because no matter what the true value of p is, all observers would note that they themselves have evolved, so our observation that we have evolved seems to offer no evidence one way or the other about p. But the jury is still out on this somewhat subtle issue, which seems to hinge on the choice between the so-called self-sampling and self-indication assumptions in the study of observer selection effects (Armstrong 2011, Häggström 2016, Bostrom 2002).

If we accept the parameter q as a guide to humanity's prospects of making it all the way to becoming a super-technological civilization, then the most relevant quantity to look at is the expected value of q under the posterior distribution. In particular, we are interested in how that expected value changes when we switch from the posterior we get after just seeing the great silence to the one that also incorporates the observation of primitive or human-level life on one planet.

Figure 1 shows the effect of one observation of primitive life, where we have taken the number of planets (experiments described by parameters r, s, q) to vary. First, we see that only observing Fermi's silence gradually lowers the expected value of q with an increasing number of planets. This can be understood from that the Bayesian
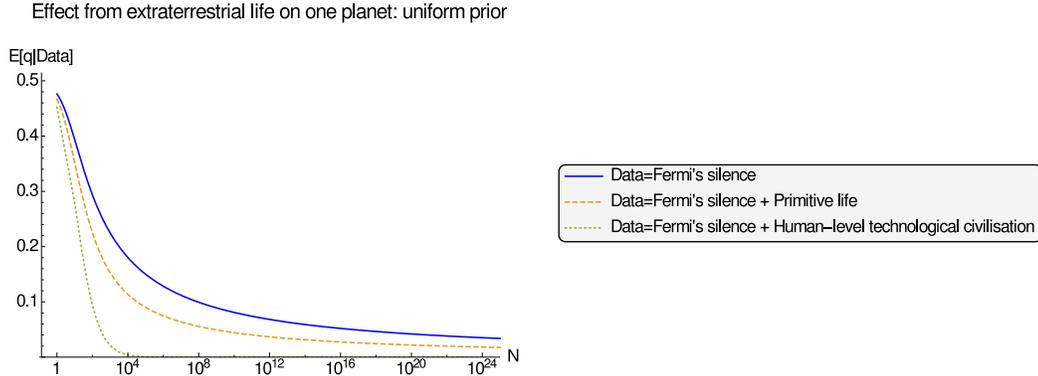
Figure 1: The effect of extraterrestrial life on q with a uniform prior for r, s, q on $[0,1]^3$.

posterior becomes proportional to $(1 - rsq)^N$, and with N failed experiments getting bigger, it makes the posterior reflect that one or more of r, s and q have to be small. Second, we see the large effect that an additional observation of primitive life has on the posterior, shifting the posterior belief on q much closer to zero. This can be understood as the new observation shifting probability in the posterior towards larger values of r, and taken together with the observations from Fermi's silence restricting rsq to be small, this has to lower the other parameters which decreases the expected value. The same line of reasoning holds for observing human-level life, with belief shifted proportional to rs, making the effect on q much more drastic. The results are in line with what we could expect from the preceding discussion, and shows one way to quantify the Great Filter argument. Analogous calculations can be made for the cases of the discoveries of extinct primitive life (a probability $r(1 - s)$ event) and an extinct human-level civilization (a probability $rs(1 - q)$ event).

But this is all for one particular choice of prior: uniform distribution on $[0,1]^3$. As one of us has argued earlier (Häggström 2007), uniform distribution is not in general a hallmark of objectivity, but just a model assumption among many other possibilities, whence unreflected and perfunctory use of it is bad practice. In this case, it may be argued that uniform distribution attaches unreasonably small probabilities to very small values of the parameters. For instance, it is not a priori implausible to imagine

a universe in which biogenesis is possible (as it clearly is, or else we would not exist) but requires some very low probability event, such as the chance assembly of some specific and rather long RNA molecule (allowing biological evolution which depends on replication to take over and make rapid progress by becoming the dominating driver). This could easily imply a value of r less than, say, 10^{-50}, but uniform distribution assigns a mere 10^{-50} probability to the event that r takes such a small value, which is just too small to reflect our taking the possibility seriously. A distribution that takes the possibility of very small parameter values more reasonably into account is the log-uniform, which was suggested in a similar setting by Tegmark (Tegmark 2014). A log-uniform distribution on $[0, 1]$ has probability density proportional to $\frac{1}{x}$. Unfortunately, $\frac{1}{x}$ blows up near $x = 0$ in such a way that $\int_0^1 \frac{1}{x} dx = \infty$, so we have to truncate the distribution near 0. Somewhat arbitrarily, we take the cutoff to be 10^{-100}, giving r density $\frac{1}{Cx}$ on $[10^{-100}, 1]$, where $C = \int_{10^{-100}}^0 \frac{1}{x} dx = 100 \ln(10)$ is a normalizing constant to make it a probability measure. Independently, we let s and q have the same distribution, so that the full prior is concentrated on $[10^{-100}, 1]^3$ with density $\frac{1}{C^3 xyz}$.

As far as the influence of discovering extraterrestrial life on the expected value of q, this prior gives qualitatively similar results as the uniform prior: in Figure 2, we see that, similarly to Figure 1, observing primitive life always lowers the expected value of q. Again, the effect on q by an observation of a human-level civilization is more drastic. Starting out from different absolute levels of expected value reflects that we start out from the prior with much larger weight on small values. However, the remaining reasoning goes the same as the model of failures in the Great Filter and success on one planet has a similar effect with the new prior.

In the two priors tried so far, the parameters r, s and q have been taken to be independent. It is not clear that this is the most reasonable choice to make. One way to reason is to suspect that all or most universes in some (real or hypothetical) multiverse are either generally amenable to producing complexity, or generally more sterile (much like what seems to be the case with, e.g., cellular automata (Wolfram 2002)). In the former case, all of r, s and q can be expected to be reasonably large,
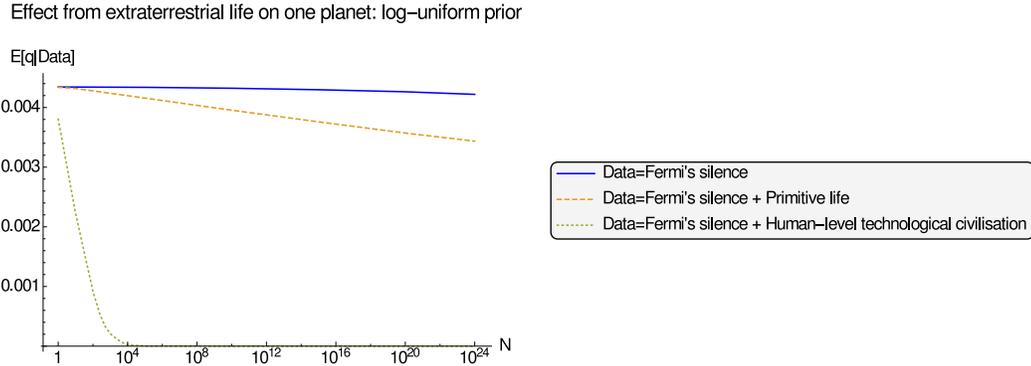
Figure 2: The effect of extraterrestrial life on q with a log-uniform prior for r, s, q in $[0, 1]^3$

while in the latter case they can all be expected to be near 0. This suggests that in the prior, the parameters should be positively correlated. For our next prior, we shall consider the extreme case where they are all lined up on the diagonal $L = \{(x, y, z) \in [10^{-100}, 1]^3 : x = y = z\}$, each log-uniformly distributed as above, but no longer independent of each other. This time, the result of discovering extraterrestrial life will be rather different: in Figure 3, we see that observing extraterrestial life has a positive effect on our expectation of q. This can be understood since the parameters are correlated: one instance of life on a lower level of complexity would have the statistical effect to increase our estimates of s and q as well.

A fair criticism against this last prior is that it dogmatically confines the triple (r, s, q) to lie on the diagonal L, thus leaving huge parts of the space $[0, 1]^3$ with zero probability. In the Appendix, we show that the example can be modified in such a way that the prior is dense all over $[0, 1]^3$ while preserving the same qualitative behavior as regards the effect of discovering extraterrestrial life on the expected value of q. Thus, we have quantitatively demonstrated that what we learn about q and in which direction belief shifts after observing extraterrestrial life can depend on which prior we use. This in turn highlights the problem of understanding to which degree the universe is in general amenable to produce complexity on various levels. Findings for or against correlation between levels, such as theoretical results in multiverse models
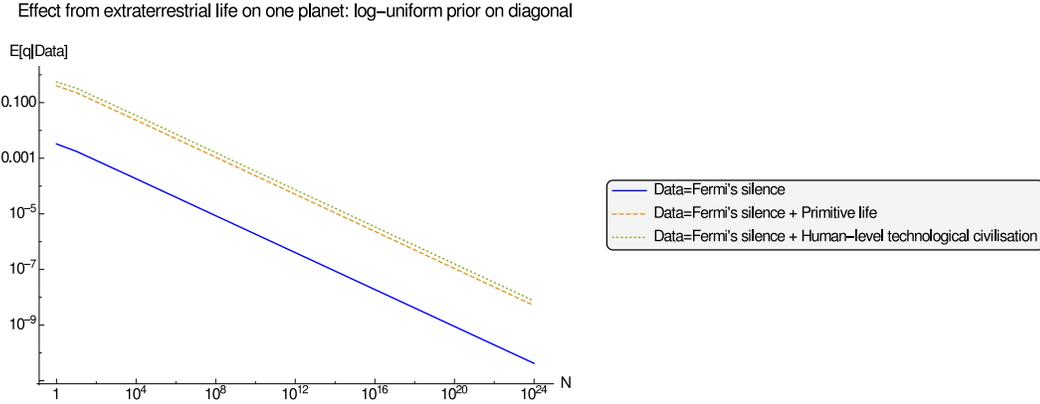
9

Effect from extraterrestrial life on one planet: log–uniform prior on diagonal

Figure 3: The effect of extraterrestrial life on q with a log-uniform prior for r, s, q on the diagonal $L = \{(x, y, z) \in [10^{-100}, 1]^3 : x = y = z\}$.

(Tegmark 2014), could have an effect on which conclusion results from the Great Filter argument.

3 Conclusions

In summary, we still think that the intuition about the alarming effect of discovering extraterrestrial life expressed by Hanson (1998) and Bostrom (2008) has some appeal. In our Bayesian analysis, our first two priors (independent uniform, and independent log-uniform) support it. The third one (perfectly correlated log-uniform), however, contradicts it, and while we find the prior a bit too extreme to make a very good choice, this shows that some condition on the prior is needed to obtain qualitative conclusions about the effect on q of discovering extraterrestrial life.

A final word of caution: While a healthy dose of critical thinking regarding the choice of Bayesian prior is always to be recommended, the case for epistemic humility is especially strong in the study of the Fermi paradox and related "big questions". In more mainstream scientific studies, circumstances are often favorable, either through the existence of a solid body of independent evidence in support of the prior, or through the availability of sufficient amounts of data that one can reasonably hope that the effects of the prior are (mostly) washed out in the posterior. In the present

10

setting we have neither, so all conclusions from the posterior should be viewed as highly tentative.

Acknowledgement. We thank Thomas Ericsson for helpful comments on numerical computation of the posterior.

References

Aldous, D. J. (2012), 'The great filter, branching histories and unlikely events', *The Mathematical Scientist* **37**(1), 55–64.

Armstrong, S. (2011), 'Anthropic decision theory', *arXiv preprint arXiv:1110.6437* .

Armstrong, S. & Sandberg, A. (2013), 'Eternity in six hours: Intergalactic spreading of intelligent life and sharpening the fermi paradox', *Acta Astronautica* **89**, 1–13.

Bostrom, N. (2002), *Anthropic bias: Observation selection effects in science and philosophy*, Routledge, New York.

Bostrom, N. (2008), 'Where are they? Why I hope the search for extraterrestrial life finds nothing', *MIT Technology Review* pp. 72–78.

Bostrom, N. (2014), *Superintelligence: Paths, dangers, strategies*, Oxford University Press, Oxford.

Bostrom, N. & Cirkovic, M. M. (2008), *Global catastrophic risks*, Oxford University Press, Oxford.

Brandt, T. D. & Spiegel, D. S. (2014), 'Prospects for detecting oxygen, water, and chlorophyll on an exo-earth', *Proceedings of the National Academy of Sciences* **111**(37), 13278–13283.

Cassan, A., Kubas, D., Beaulieu, J.-P., Dominik, M., Horne, K., Greenhill, J., Wambsganss, J., Menzies, J., Williams, A., Jørgensen, U. G. et al. (2012), 'One or more bound planets per milky way star from microlensing observations', *Nature* **481**(7380), 167–169.

Ćirković, M. (2009), 'Fermi's paradox: The last challenge for copernicanism?', *Serbian Astronomical Journal* **178**, 1–20.

Cox, D. & Hinkley, D. (1979), *Theoretical statistics*, Chapman and Hall, London.

Griffith, R. L., Wright, J. T., Maldonado, J., Povich, M. S., Sigurdsson, S. & Mullan, B. (2015), 'The ĝ infrared search for extraterrestrial civilizations with large energy supplies. iii. the reddest extended sources in wise', *The Astrophysical Journal Supplement Series* **217**(2), 25.

Häggström, O. (2007), 'Uniform distribution is a model assumption'. http://www.math.chalmers.se/~olleh/reply_to_Dembski.pdf.

Häggström, O. (2016), *Here Be Dragons: Science, Technology and the Future of Humanity*, Oxford University Press, Oxford. To appear.

Hanson, R. (1998), 'The great filter – are we almost past it?'. http://hanson.gmu.edu/greatfilter.html.

Hart, M. (1975), 'Explanation for the absence of extraterrestrials on earth', *Quarterly Journal of the Royal Astronomical Society* **16**, 128–135.

Martin, J. (2006), *The meaning of the 21st century: A vital blueprint for ensuring our future*, Transworld, London.

Pamlin, D. & Armstrong, S. (2015), *Global Challenges: 12 Risks that Threaten Human Civilization*, Global Challenges Foundation, Stockholm.

Petigura, E. A., Howard, A. W. & Marcy, G. W. (2013), 'Prevalence of earth-size planets orbiting sun-like stars', *Proceedings of the National Academy of Sciences* **110**(48), 19273–19278.

Quintana, E. V., Barclay, T., Raymond, S. N., Rowe, J. F., Bolmont, E., Caldwell, D. A., Howell, S. B., Kane, S. R., Huber, D., Crepp, J. R. et al. (2014), 'An earth-sized planet in the habitable zone of a cool star', *Science* **344**(6181), 277–280.

Rees, M. (2003), *Our Final Century: Will the Human Race Survive the Twenty-first Century?*, William Heinemann, London.

Salsburg, D. (2001), 'The lady tasting tea: How statistics revolutionized science in the twentieth century'.

Tegmark, M. (2014), *Our mathematical universe: my quest for the ultimate nature of reality*, Allen Lane, London.

Webb, S. (2002), *If the universe is teeming with aliens... where is everybody?: fifty solutions to the Fermi paradox and the problem of extraterrestrial life*, Copernicus Books, New York.

Wolfram, S. (2002), *A new kind of science*, Wolfram media, Champaigne, IL.

Appendix

To demonstrate our claim that the expected value of q can increase in response to discovering extraterrestrials also in cases where the prior is dense in $[0,1]^3$, we need some terminology. Fix N. We write $\mathbb{P}_0$ for a probability measure corresponding to picking (r,s,q) on the diagonal L as in our log-uniform diagonal example, plus doing the appropriate Bernoulli trials for N independent planets. We write $\mathbb{P}_1$ for the analogous thing, but with picking (r,s,q) according to uniform distribution on $[0,1]^3$. For $\varepsilon > 0$, we let $\mathbb{P}_\varepsilon$ be the convex combination $\varepsilon\mathbb{P}_1 + (1-\varepsilon)\mathbb{P}_0$, and note that since the distribution of (r,s,q) is dense in $[0,1]^3$ under $\mathbb{P}_1$, the same is true under $\mathbb{P}_\varepsilon$. Write $\mathbb{E}_0$, $\mathbb{E}_1$ and $\mathbb{E}_\varepsilon$ for expectation under respectively $\mathbb{P}_0$, $\mathbb{P}_1$ and $\mathbb{P}_\varepsilon$.

Let A be any event satisfying

$$\mathbb{P}_0(A) > 0 \,. \tag{3}$$

Two examples of such A is A', defined as observing the great silence (N independent Bernoulli (rsq) variables all taking value 0), and A'', defined as A' plus discovering primitive life on a single planet. We have seen that

$$\mathbb{E}_0[q|A'] < \mathbb{E}_0[q|A''] \tag{4}$$

and wish to show that

$$\mathbb{E}_\varepsilon[q|A'] < \mathbb{E}_\varepsilon[q|A''] \tag{5}$$

for sufficiently small $\varepsilon > 0$. To get from (4) to (5) it suffices to show that

$$\lim_{\varepsilon \to 0} \mathbb{E}_\varepsilon[q|A] = \mathbb{E}_0[q|A] \tag{6}$$

for all A satisfying (3). Writing B for the event that (r, s, q) sits on the diagonal $r = s = q$, and decomposing $\mathbb{E}_\varepsilon[q|A]$ as

$$\mathbb{E}_\varepsilon[q|A] = \mathbb{P}_\varepsilon(B|A)\mathbb{E}_\varepsilon[q|A, B] + \mathbb{P}_\varepsilon(\neg B|A)\mathbb{E}_\varepsilon[q|A, \neg B]$$

we first note that conditioning $\mathbb{P}_\varepsilon$ on the event B yields $\mathbb{P}_0$, and that conditioning $\mathbb{P}_\varepsilon$ on the event $\neg B$ yields $\mathbb{P}_1$, so that

$$\mathbb{E}_\varepsilon[q|A] = \mathbb{P}_\varepsilon(B|A)\mathbb{E}_0[q|A] + \mathbb{P}_\varepsilon(\neg B|A)\mathbb{E}_1[q|A]. \tag{7}$$

As to the factor $\mathbb{P}_\varepsilon(B|A)$, we get using Bayes' Theorem that

$$
\begin{aligned}
\mathbb{P}_\varepsilon(B|A) &= \frac{\mathbb{P}_\varepsilon(B)\mathbb{P}_\varepsilon(A|B)}{\mathbb{P}_\varepsilon(B)\mathbb{P}_\varepsilon(A|B) + \mathbb{P}_\varepsilon(\neg B)\mathbb{P}_\varepsilon(A|\neg B)} \\
&= \frac{(1 - \varepsilon)\mathbb{P}_\varepsilon(A|B)}{(1 - \varepsilon)\mathbb{P}_\varepsilon(A|B) + \varepsilon\mathbb{P}_\varepsilon(A|\neg B)} \\
&= \frac{(1 - \varepsilon)\mathbb{P}_0(A)}{(1 - \varepsilon)\mathbb{P}_0(A) + \varepsilon\mathbb{P}_1(A)}
\end{aligned}
$$

which tends to 1 as $\varepsilon \to 0$. It follows also that $\lim_{\varepsilon \to 0} \mathbb{P}_\varepsilon(\neg B|A) = 0$. Sending $\varepsilon \to 0$ in the right hand side of (7) therefore yields (6), and (5) follows as desired.