Lu Replies: In the preceding Comment [1], Alvarez-Madrigal mainly argues that "since the correlation coefficient ($r = -0.52$) is too low, cosmic ray (CR) intensity is not the principal variable to explain the total ozone variations and/or the ozone hole severity, because it explains only about 27% (r^2) of the total ozone variation, in a linear relationship, so that other causes should be used to predict most of the variation of the ozone." However, it should be noted that the CR-driven-electron-reaction (CRE) mechanism of halogenated molecules for the ozone hole has never considered CRs as the only factor for the ozone hole [2–5], and the poor linear correlation in CR-polar ozone loss has been well discussed and replaced by a quadratic equation in [5]. The latter is not cited in the Comment [1]. And the argument that the CR intensity is not the principal variable for polar ozone loss is incorrect, since a low Pearson correlation coefficient is well known to only indicate a low *degree* of linear correlation of between two variables (a poor linear correlation).

Since its birth one decade ago, the CRE mechanism has consistently proposed that both CRs and CFCs are major culprits for the ozone hole [2–5]. Moreover, it was shown in the original Letter [4] and in a recently published paper [5] that observed data do not agree with the pure CR mechanism that assumes CRs as the *only* variable to the ozone hole.

The Letter [4] showed a main observation of a *long-term* time correlation between CR intensity and O_3 loss in the Antarctic ozone hole over 11-year CR cycles. It was also noted that in the CRE mechanism the O_3-depleting reactions depend on halogen concentrations, CR intensity, and polar stratospheric cloud ice (to hold the electrons) in the stratosphere. From 1992 until now, the Antarctic O_3 loss has shown a pronounced correlation with the CR intensity because the total halogen amount of the stratosphere, particularly those of CFCs, has not changed significantly. In contrast, such a time correlation was hardly seen during the 1980s because the halogen loading increased dramatically, and thus the ozone showed a drastic decreasing trend blurring the CR-ozone correlation. The study also led to direct predictions of one polar O_3 loss peak (due to the CR peak) in 2008–2009 and another peak around 2019–2020. With the CR intensity for 2008 and the assumption that no significant decreases of halogen loading occurred in the stratosphere, the best-fit linear equation from Fig. 4 (of Ref. [4]) gave a variation $\Delta(O_3) \approx -14.5\%$ for the October mean total O_3 over Antarctica at latitudes of 60°–90° S. It was stated that, "Although atmospheric dynamics and meteorological conditions could influence the CR effect and lead to large fluctuations of the O_3 hole from year to year, a long-term trend of the polar O_3 loss (hole) is predictable." Thus, the linear fit was obviously limited to the condition that there was no significant variation in the stratospheric halogen amount (valid for a limited period), which was indeed referred to as the "long term" of 1990–2008 for the polar ozone hole variation [4].

After publishing the Letter [4], I made efforts to obtain a quantitative expression of the CRE model, since there was one major problem that the *linear* correlation could not give a good fit to all observed data from the 1950s to 2008. Then, a simplified equation from the CRE model was derived: the observed total ozone ($[O_3]_i$) in the spring Antarctic hole can be well fitted by $[O_3]_i = [O_3]_0 \times [1 - kI_iI_{i-1}C_i]$, where I_i is the CR intensity in the ith year, C_i the equivalent effective stratospheric chlorine, and $[O_3]_0$ the total O_3 in the polar stratosphere when $C_i = 0$ and k is a constant. This result has been published in a relatively comprehensive article on the CRE model in Ref. [5]. Unlike the linear fit, the CRE equation showing a nearly quadratic relationship with CR intensity can now give good fits to the observed data of not only total O_3 but also of stratospheric cooling due to ozone loss over Antarctica since the 1950s [5].

In summary, one should not ignore the fact that the poor linearity in correlation between CR intensity and polar ozone loss and other possible factors affecting the ozone hole had been extensively discussed and a quantitative nonlinear CRE equation had been given in [5]. These facts lead to the fact that there is no new physical insight in the Comment [1].

Qing-Bin Lu
Department of Physics and Astronomy
University of Waterloo
Waterloo, Ontario, Canada

Received 10 August 2010; published 15 October 2010
DOI: 10.1103/PhysRevLett.105.169802
PACS numbers: 92.70.Cp, 34.80.Ht, 82.65.+r, 89.60.−k

[1] M. Alvarez-Madrigal, preceding Comment, Phys. Rev. Lett. **105**, 169801 (2010).
[2] Q.-B. Lu and T. E. Madey, J. Chem. Phys. **111**, 2861 (1999).
[3] Q.-B. Lu and L. Sanche, Phys. Rev. Lett. **87**, 078501 (2001).
[4] Q.-B. Lu, Phys. Rev. Lett. **102**, 118501 (2009).
[5] Q.-B. Lu, Phys. Rep. **487**, 141 (2010).

