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ORIGINAL RESEARCH

Solar Activity Is Associated With Diastolic and Systolic Blood Pressure in Elderly Adults

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BACKGROUND: Since solar activity and related geomagnetic disturbances modulate autonomic nervous system activity, we hypothesized that these events would be associated with blood pressure (BP).

METHODS AND RESULTS: We studied 675 elderly men from the Normative Aging Study (Boston, MA) with 1949 BP measurements between 2000 and 2017. Mixed-effects regression models were used to investigate the association of average 1-day (ie, day of BP measurement) to 28-day interplanetary magnetic field intensity, sunspot number, and a dichotomized measure of global geomagnetic activity (K_p index) in 4-day increments with diastolic and systolic BP. We adjusted for meteorological conditions and other covariates associated with BP, and in additional models adjusted for ambient air pollutants (particulate matter with an aerodynamic diameter ≤2.5 μm, black carbon, and particle number) and ambient particle radioactivity. There were positive associations between interplanetary magnetic field, sunspot number, and K_p index and BP that were greatest with these exposures averaged over 16 through 28 days before BP measurement. An interquartile range increase of 16-day interplanetary magnetic field and sunspot number and higher K_p index were associated with a 2.5 (95% CI, 1.7–3.2), 2.8 (95% CI, 2.1–3.4), and 1.7 (95% CI, 0.8–2.5) mm Hg increase, respectively, for diastolic BP as well as a 2.1 (95% CI, 0.7–3.6), 2.7 (95% CI, 1.5–4.0), and 0.4 (95% CI, –1.2 to 2.1) mm Hg increase, respectively, for systolic BP. Associations remained after adjustment for ambient air pollutants and ambient particle radioactivity.

CONCLUSIONS: Solar activity and solar-driven geomagnetic disturbances were positively associated with BP, suggesting that these natural phenomena influence BP in elderly men.

Key Words: aged ■ air pollutants ■ autonomic nervous system ■ blood pressure ■ solar activity

The Earth's magnetic field protects living organisms from long-term, harmful extra-terrestrial radiation. Despite this protective shield, solar activity can cause geomagnetic disturbances (GMD), disruptions to the Earth's natural magnetic field oscillations, and can impact autonomic nervous system activities,[1,2] which can, in turn, directly and indirectly play a role in initiating and sustaining high blood pressure (BP).[3] Numerous pathogenic risk factors such as genetic predisposition,[4] physical activity,[5] and diet[6] have been identified to play key roles in the development of hypertension. A recent review[7] highlighted the role of environmental factors, such as temperature, altitude, latitude, and air pollutants, in elevating BP, but few studies considered solar activity and GMD as risk factors for the development of hypertension or transient increases in BP. In those that have,[8,9] the findings suggest that individuals have elevated BP several days before and after magnetic storms.

To gain insight and provide awareness into the association between solar activity and BP in elderly men, a vulnerable population at high risk for cardiovascular

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CLINICAL PERSPECTIVE

What Is New?

- Solar and geomagnetic activity were associated with increases in blood pressure in a large cohort of predominantly White, elderly men.
- The association with blood pressure was similar to or greater than that of particulate pollution and of radioactivity associated with ambient particles.
- The association of solar and geomagnetic activity with blood pressure was independent of these pollutants.

What Are the Clinical Implications?

- These findings suggest that natural phenomena linked to the solar cycle contributes to increases in blood pressure and, therefore, may influence hypertension management.

Nonstandard Abbreviations and Acronyms

BC	black carbon
DBP	diastolic blood pressure
GMD	geomagnetic disturbances
IMF	interplanetary magnetic field
NAS	Normative Aging Study
$PM_{2.5}$	particulate matter mass concentration with an aerodynamic diameter ≤2.5 μm
PN	particle number
SBP	systolic blood pressure
SSN	sunspot number

disease,[10] we conducted a repeated measures analysis to examine the association of average 1-day (ie, day of BP measurement) to 28-day solar activity and GMD with BP among elderly men in Boston, MA who had between 1 and 8 health assessments over 17 years. We hypothesized that solar and geomagnetic activity is positively associated with systolic blood pressure (SBP) and diastolic blood pressure (DBP).

METHODS

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Study Population

The study was conducted among healthy men born between 1884 and 1945 and enrolled in the NAS (Normative Aging Study) (Boston, MA), a cohort established by the US Veterans Administration in 1963 as previously described.[11,12] Participants were recruited through radio and newspaper advertisements and outreach to employers and were asked to return for examination in intervals of 3 to 5 years for a standardized health assessment. At enrollment, participants were free of heart diseases, cancer, peptic ulcer, gout, hypertension, diabetes, pancreatitis, cirrhosis, recurrent asthma, bronchitis, and sinusitis. There were 765 participants and 2443 clinical observations in the NAS cohort during 2000 to 2017, which corresponds to the time period when solar and air pollution exposures were consistently measured and available. Data on other covariates were largely complete (<1% missingness) except salt intake (19% missingness) and resting pulse (1% missingness). We restricted our study population to those with complete data (ie, complete exposure, outcome, and covariates) to obtain the final sample size of 675 participants and 1949 clinical observations.

The Institutional Review Boards at the Harvard T.H. Chan School of Public Health and at the Veterans Administration Boston Healthcare System approved all procedures in this study. Written informed consent was obtained from each participant.

Health Outcomes

SBP and DBP were measured in each arm using a standard cuff with the participant in the seated position following a seated patient history. Further details on the methodology can be found in previously published studies.[13,14] Right and left arm SBP and DBP readings were averaged for analyses. If BP reading was only available in one arm and not the other, that reading was used.

Solar Activity and GMD Assessment

We used sunspot number (SSN) and interplanetary magnetic field (IMF) intensity as indicators of solar activity along with K_p index as an indicator of GMD. These data were obtained from the NASA Goddard Space Flight Center[15] and were converted from Coordinated Universal Time to Eastern Time, the time zone in Boston, MA, as these exposures vary based on geographic location and day. Sunspots are dark spot areas of concentrated magnetic fields on the Sun, and SSN is strongly associated with the intensity of solar wind plasma and solar radiation emissions, including ultraviolet and soft X-rays.[16,17] SSN data used in this study were measured visually and hourly using the Zurich Sunspot number and were averaged over 24-hour periods by the Solar Influences Data Analysis Center in Belgium.[18] Changes in SSN impact the Sun's magnetic field, and solar wind that represent a flow of charged particles can transmit these effects across the solar system, thus affecting space weather, and is measured as IMF. IMF is monitored continuously, and daily averages are derived from hourly values. IMF intensity includes the total IMF strength in several directions, including the north-south component that is indicative of the occurrence and progression of auroral storms.[19] Solar winds that reach the Earth's surface cause short-term variations in the Earth's magnetic field.[20] These GMD are measured by K_p index, which were previously shown to be directly related to the strength of magnetospheric convection,[21] and ranges from 0 (no disturbance) to 9 (extreme storm).

Because solar activity influences solar winds before impacting the geomagnetic environment of Earth, we expect the effect of solar activity to be delayed by at least several days.[22] Still, there is limited understanding of when the most relevant exposure window of geomagnetic activity for BP would be. Therefore, we explored average 1-day (ie, day of BP measurement) to 28-day exposure windows in 4-day increments.

Ambient Air Pollutants and Particle Radiation

Ambient air fine particle pollutants (particulate matter mass concentration with an aerodynamic diameter ≤2.5 μm [$PM_{2.5}$], black carbon [BC], and particle number [PN]) and ambient particle radioactivity, which refers to β-radiation measured in ambient particles, have been previously shown to be associated with elevated BP.[23,24] Daily, 24-hour averaged measurements of $PM_{2.5}$, BC, and PN were obtained from the Harvard Air Pollution Monitoring Supersite in Boston, MA. $PM_{2.5}$ was measured with a tapered-element oscillating microbalance (Model 1400A; Rupprecht & Patashnick Co. Inc., Albany, New York). BC was measured using an Aethalometer (Model AE-16; Magee Scientific Corp., Berkeley, California), and PN was measured with a condensation particle counter (Model 3022A; TSI, Inc., Shoreview, Minnesota). Particle β-radiation was obtained from US EPA's RadNet system, which collects and monitors radioactivity in total suspended particles. Details about sampling and imputation methods are described by Nyhan et al.[12] Particle β-activity values were natural-log transformed because of its skewed distribution and hereafter denoted as log(β).

Statistical Analysis

For each exposure window of interest, we used the following mixed-effects model with a subject-specific intercept to evaluate the effect of each solar activity and GMD exposure variable on BP and to account for longitudinal correlation among BP readings from the same participant:

$$Y_{ij} = \beta_0 + \beta_1 X_{1ij} + \ldots + \beta_k X_{kij} + \beta_{k+1} E_{ij} + b_i + \varepsilon_{ij}$$

For individual i at clinical visit j, Y_{ij} is the outcome (SBP or DBP), X_{1ij} to X_{kij} denote the covariates, and E_{ij} is the same-day or moving average of the exposure (IMF, SSN, or K_p index). In this model, b_i is the subject-specific intercept that allows for correlation of measurements within participants. Estimated associations with BP were reported for an interquartile range increase in exposure to enable comparison across geomagnetic activity and air pollutant exposure variables, where an interquartile range was calculated by taking the difference between the 75th and 25th percentile of exposure measured on the days of BP observation. Solar activity measures, SSN and IMF, were treated as continuous covariates, while K_p index was dichotomized based on the 75th percentile value separately for each exposure window.

We adjusted for several covariates based on prior knowledge in all models. We controlled for the 24-hour average temperature (°C) and relative humidity (%) in Boston, MA on the day of BP measurement as reported by the National Oceanic Atmospheric Administration's National Centers for Environmental Information.[25] Seasonality was included in our models using sine and cosine terms as follows:

$$\sin\left(2 \times \pi \times \frac{\text{day}}{365}\right) \text{ and } \cos\left(2 \times \pi \times \frac{\text{day}}{365}\right).$$

We also adjusted for several covariates that may be associated with BP but are unrelated to the solar-related exposures: age (continuous), body mass index (continuous), race (White/Black), pulse (continuous), fasting plasma glucose (continuous), smoking status (current/former/never), pack-years of cumulative smoking (continuous), alcohol consumption (typically ≥2 drinks per day/typically <2 drinks per day), physician-diagnosed diabetes (yes/no), income (continuous), day of the week (categorical), use of statin drugs (yes/no), use of antihypertensive medication (yes/no), and salt intake (any/none). Participants who self-reported use of α-blockers, β-blockers, calcium channel blockers, diuretics, angiotensin-converting enzyme inhibitors, angiotensin receptor antagonists, or other vascular agents prescribed for hypertension were considered to be taking antihypertensive medication. Salt intake was ascertained by summing over the servings of salt added to staple foods, soup, meat, and vegetables. These variables were obtained from questionnaires used during the clinical visit as described in previous studies.[26]

Because follow-up availability may be nonrandom, common in longitudinal studies, we additionally used inverse probability weighting to account for this potential selection bias by regressing the probability of having a next visit based on the covariates available at the previous visits (Data S1). To increase precision at the cost of minimal bias, we assigned weights over the 99.5 percentile and below the 0.5 percentile to the 99.5 and 0.5 percentile values, respectively.[27]

In light of previous evidence of the effect of air pollutants on BP among elderly individuals,[7,28–30] we conducted analyses to estimate the independent effect of solar and magnetic factors on BP by adjusting for the moving average window of each air pollutant and particle radioactivity that produced the strongest effect. We fitted separate linear mixed-effects models for each average 1-day (ie, day of BP measurement) to 28-day exposure window for each air pollutant, excluding the solar activity variable, to identify the exposure window that produced the strongest effect. All analyses were performed using R software 4.0.0.

RESULTS

Almost all of the participants were White men (98.1%) (Table 1). At this study baseline, participants had a mean±SD age of 72.8±6.6 years and body mass index of 28.1±3.9 kg/m^2. While only 4.5% were current smokers, the majority of men were former smokers (64.6%). Mean SBP and DBP at baseline were 131.0 and 75.9 mm Hg, respectively. As expected in an aging cohort, some clinical characteristics became more prevalent in subsequent visits. Approximately 12% of men had physician-diagnosed diabetes at study baseline, while18% of men had it in subsequent visits. The proportion of men who used statin drugs and antihypertensive medication also increased over time (study baseline versus subsequent visit), 35.0% versus 61.9% and 64.1% versus 77.9%, respectively. The mean±SD (minimum, maximum) average outdoor air temperature was 13.4±8.8 °C (–12.1 °C, 32.3 °C). Summary statistics of the 3 indices of solar and geomagnetic activity along with ambient air pollutants and particle radioactivity exposures are presented in Table 2.

IMF and SSN were positively associated with SBP and DBP for exposure windows ranging from 1 to 28 days (Figures 1 and 2). The effect estimates of IMF on SBP and DBP increased slightly through the 16-day exposure window and then plateaued, whereas the effect of SSN was similar across all exposure windows. K_p index was also positively associated with DBP but not with SBP. Interquartile range increases in 16-day IMF and SSN along with higher K_p index exposure were associated with a 2.5 (95% CI, 1.7–3.2), 2.8 (95% CI, 2.1–3.5), and 1.7 (95% CI, 0.8–2.5) mm Hg increase in DBP, respectively. For SBP, the corresponding effect estimates for the average 16-day IMF and SSN were 2.1 (95% CI, 0.7–3.6) and 2.7 (95% CI, 1.5–4.0) mm Hg, respectively. Numerical effect estimates for SBP and DBP are provided in Tables S1 and S2, respectively.

$PM_{2.5}$ was not associated with either SBP or DBP (Figures S1 and S2, respectively). BC and log(β) were

Table 1. Characteristics of NAS Cohort 2000 to 2017 at Baseline and Over All Clinical Examinations

	Baseline (n=675)	Other visits (n=1274)	All visits (n=1949)
DBP, mm Hg	75.9±9.5	67.6±9.4	70.5±10.2
SBP, mm Hg	131.0±16.6	128.0±17.5	129.0±17.2
Age, y	72.8±6.6	78.5±6.3	76.5±7.0
BMI, kg/m^2	28.1±3.9	27.8±4.2	27.9±4.1
Cumulative smoking, pack-years	30.2±25.5	27.3±22.0	28.3±23.3
Pulse, bpm	71.0±7.4	68.1±10.9	69.1±10.0
Fasting plasma glucose, mg/dL	107.0±24.8	103.0±20.5	104.0±22.1
Race			
White*	662 (98.1)	1249 (98.0)	1911 (98.1)
Black†	13 (1.9)	25 (2.0)	38 (1.9)
Salt intake	365 (54.1)	591 (46.4)	956 (49.1)
≥2 drinks/d	127 (18.8)	219 (17.2)	346 (17.8)
Smoking status			
Current	31 (4.6)	43 (3.4)	74 (3.8)
Former	436 (64.6)	826 (64.8)	1262 (64.8)
Never	208 (30.8)	405 (31.8)	613 (31.5)
Physician-diagnosed diabetes	83 (12.3)	231 (18.1)	314 (16.1)
Statin drugs	236 (35.0)	789 (61.9)	1025 (52.6)
Antihypertensive medication	433 (64.1)	993 (77.9)	1426 (73.2)

Values of continuous variables were reported as mean±SD, and values of categorical variables were reported as n (%).

*Both non-Hispanic (n=1899) and Hispanic White participants (n=12) were included.

†Both Black (n=34) and Hispanic Black participants (n=4) were included.

Table 2. Distributions of Solar Activity Variables and Air Pollutants on the Day of BP Measurement

Exposure, unit	Median (IQR)	Range
Solar activity		
IMF, nT	5.3 (2.9)	1.8–29.2
SSN, sunspots	68.7 (118.7)	0.0–351.5
K_p index	465 (23.9%)*	
Air pollutants		
$PM_{2.5}$, μg/m^3	7.6 (6.6)	−0.4 to 58.4
BC, μg/m^3	0.7 (0.5)	0.1–2.5
PN, ×10^4 number/cm^3	1.8 (1.6)	0.3–9.2
log(β)†	−5.0 (0.4)	−6.2 to −4.1

BC indicates black carbon; IMF, interplanetary magnetic field; log(β), natural-log transformed particle β-activity; IQR, interquartile range; $PM_{2.5}$, particulate matter ≤2.5 μm; PN, particle number; and SSN, sunspot number.

*Reported as the count of K_p index values over the 75th percentile (2.6) (%).

†β is expressed in units of Bq/m^3.

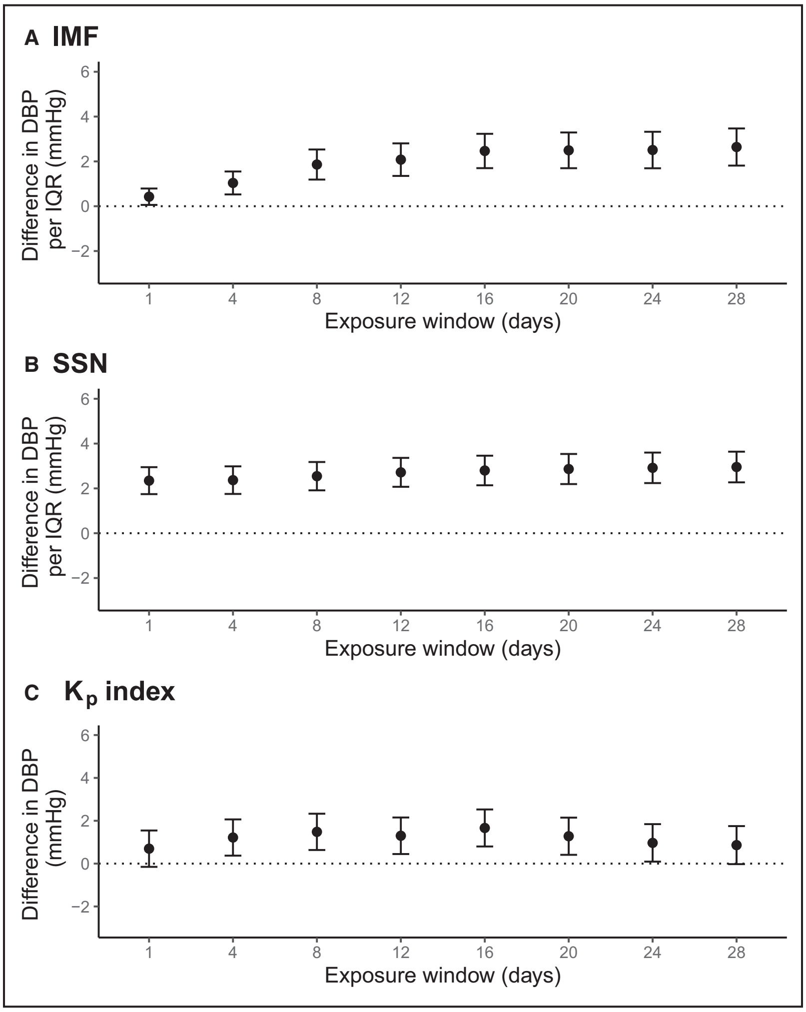

Figure 1. Association of solar and geomagnetic activity with systolic blood pressure.

A, Features interplanetary magnetic field intensity as a parameter of solar activity, and (**B**) uses sunspot number. **C**, Uses dichotomized K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The *x*-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the *y*-axis represents the difference in systolic blood pressure in mm Hg per interquartile range (IQR) increase for continuous solar activity exposures (interplanetary magnetic field and sunspot number) or above and below the 75th percentile for dichotomized K_p index. The interquartile range of each solar activity exposure is shown in Table 2. The error bars denote the 95% CIs. IMF indicates interplanetary magnetic field; IQR, interquartile range; SBP, systolic blood pressure; and SSN, sunspot number.

positively associated with DBP but not with SBP. PN was associated with both elevated SBP and DBP. Table 3 shows the exposure windows with the strongest effect of $PM_{2.5}$, BC, PN, and log(β) on BP used in the sensitivity analyses. The associations between solar activity and both SBP and DBP remained similar after adjusting for ambient air pollutants and particle radioactivity, as shown in Figures 3 and 4, respectively, and numerical effect estimates are reported in Tables S1 and S2.

As found for previous studies using the NAS cohort,[12,28] applying inverse probability weights to account for potential non-random loss to follow-up yielded essentially the same results (Figures S3 through S6).

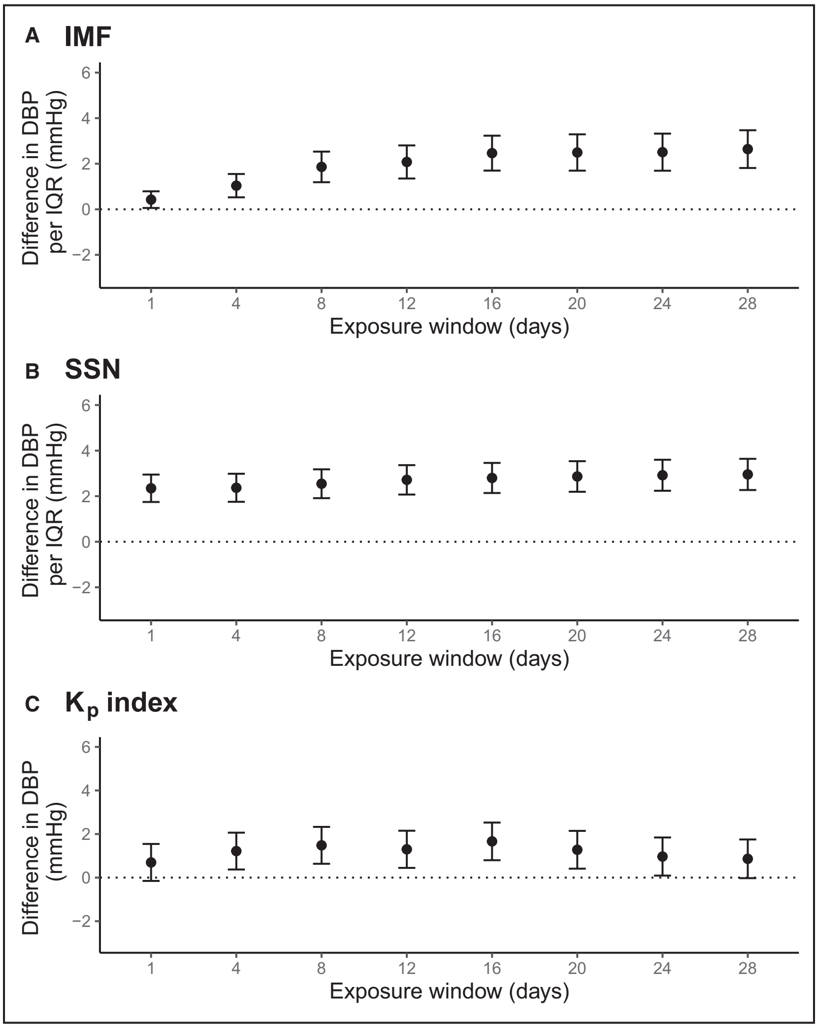

Figure 2. Association of solar and geomagnetic activity with diastolic blood pressure.
A, Features interplanetary magnetic field intensity as a parameter of solar activity, and (**B**) uses sunspot number. **C**, Uses dichotomized K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The *x*-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the *y*-axis represents the difference in DBP in mm Hg per interquartile range (IQR) increase for continuous solar activity exposures (interplanetary magnetic field and sunspot number) or above and below the 75th percentile for dichotomized K_p index. The interquartile range of each solar activity exposure is shown in Table 2. The error bars denote the 95% CIs. DBP indicates diastolic blood pressure; IMF, interplanetary magnetic field; IQR, interquartile range; SBP, systolic blood pressure; and SSN, sunspot number.

DISCUSSION

Increases in solar and geomagnetic activity were found to be associated with higher BP among elderly men in Boston, MA. The magnitude of these associations was similar to or greater than the effects of common air pollutants and remained essentially the same after adjusting for these air pollutants.

Although detailed mechanisms of how solar and geomagnetic activity acts on BP are not yet known, there are several hypothesized ways that solar activity can modulate BP via the autonomic nervous system. A recent review[31] highlighted that changes in the solar activity-induced magnetic and the electromagnetic environment around the earth can alter the 24-hour circadian rhythm. The most prominent

Table 3. Strongest Effect of Air Pollution on Blood Pressure Among Exposure Windows 1 to 28 Days

Outcome	Air pollutant	Exposure window*, d	Difference in outcome per IQR of air pollutant (95% CI), mm Hg	*P* value
DBP	$PM_{2.5}$	7	0.5 (−0.2 to 1.1)	0.15
	BC	28	1.7 (0.5–2.9)	0.01
	PN	12	3.1 (2.2–3.9)	<0.01
	log(β)	14	1.1 (0.5–1.8)	<0.01
SBP	$PM_{2.5}$	19	−0.8 (−2.3 to 0.7)	0.30
	BC	5	−0.9 (−2.5 to 0.8)	0.30
	PN	12	2.37 (0.8–4.0)	<0.01
	log(β)	1	0.6 (−0.4 to 1.6)	0.28

BC indicates black carbon; DBP, diastolic blood pressure; IQR, interquartile range; log(β), natural-log transformed particle gross β-activity; $PM_{2.5}$, particulate matter ≤2.5 μm; PN, particle number; and SBP, systolic blood pressure.

*Moving average with the strongest effect estimate.

pathway is thought to be mediated through melatonin. Specifically, the pineal gland responds to the magnetic stimuli from geomagnetic activity and leads to subsequent changes in melatonin secretion. Although the mechanism for detecting geomagnetic fluctuations has not been established in humans, circadian photoreception through cryptochrome proteins in the pineal gland has been shown in animal studies.[32] Given our findings and others[33,34] that demonstrate associations between particulate air pollution and increases in BP, it is possible that these effects may also be influenced by solar activity since it can influence ultrafine particle concentrations.[35,36]

Though limited by short follow-up periods and inadequate control for important risk factors, previous studies generally showed a positive relationship between GMD and BP.[31] Ghione et al[8] used ambulatory BP measurements among untreated patients from a hypertension outpatient clinic and found increased GMD the day of the monitoring, but not the days prior, to be correlated with DBP and SBP. Using several criteria to identify days with increased GMD, mean 24-hour DBP and SBP was greater by 6 to 8 mm Hg on days with more GMD disturbances. Dimitrova et al[9] investigated BP changes up to 3 days before and after geomagnetic storms and found that BP increased on the day before to 2 days after a geomagnetic storm. Moreover, arterial SBP and DBP increased with higher levels of geomagnetic activity. Since it can take several minutes to days for magnetic disturbances from solar activity to reach Earth, Dimitrova et al had limited ability to fully observe the effects from magnetic field disturbances since only 3 days after a geomagnetic storm was assessed. In the present study, we observed greater, cumulative effects that were greatest weeks after exposure.

Modest changes in average BP observed on the population level can have meaningful impacts on morbidity and mortality.[37–39] The magnitude of our findings about solar and geomagnetic activity are similar to those of several non-pharmacologic and pharmacologic interventions aimed at reducing BP. For example, in a randomized controlled trial among men and women ages 60 to 80 years (baseline SBP/DBP=128/71 mm Hg), SBP/DBP decreased by 3.4/1.9, 4.0/1.1, and 5.3/3.4 mm Hg for those assigned to the sodium reduction intervention, the weight loss intervention, and the combined intervention, respectively.[40] Similarly, a meta-analysis of controlled clinical trials found various plant-based diets to lower SBP by 0.57 (high-fruit and vegetable) to 5.53 (Dietary Approach to Stop Hypertension) mm Hg and to lower DBP by 0.69 (Mediterranean) to 3.78 (Dietary Approach to Stop Hypertension) mm Hg.[41] In the HOPE (Heart Outcomes Prevention Evaluation) study, a large factorial-designed clinical trial with >9500 participants where about 50% of patients had a history of hypertension, ramipril, an angiotensin-converting enzyme inhibitor, reduced SBP and DBP by 3 to 4 mm Hg and 1 to 2 mm Hg, respectively.

Our study has several limitations. First, our study population consists of predominantly White, elderly men (98.1%), and results may not be generalizable to other vulnerable populations, including elderly women and other racial/ethnic minority groups. Both SBP and DBP have been found to be higher among elderly women compared with men,[42] as sex-specific processes throughout a women's life, such as pregnancy, can modify BP.[43] Moreover, racial differences in hypertension are well-established,[44] and the present study needs to be replicated in different demographic and spatial settings and populations. Next, we used outer space parameters as exposure variables that may not adequately reflect individual exposures. Americans spend about 87% of their time indoors.[45] Although the indoor environment can provide partial protection from some outdoor exposures, electromagnetic disturbances, γ radiation, and other high energy cosmic rays can easily penetrate into the indoor spaces. Lastly, since the effects of solar activity on BP was still present for the maximal 28-day exposure window we used, future studies assessing effects after this time point are needed to better quantify longer term effects on BP and cardiovascular morbidity.

To our knowledge, this study is the first to investigate the effect of solar activity on BP among elderly men, in whom hypertension is common.[10] We explored various exposure windows and adjusted for important personal factors associated with BP, such as salt intake and diabetes,[46–48] not available for consideration in previous studies. We also considered key air pollutants

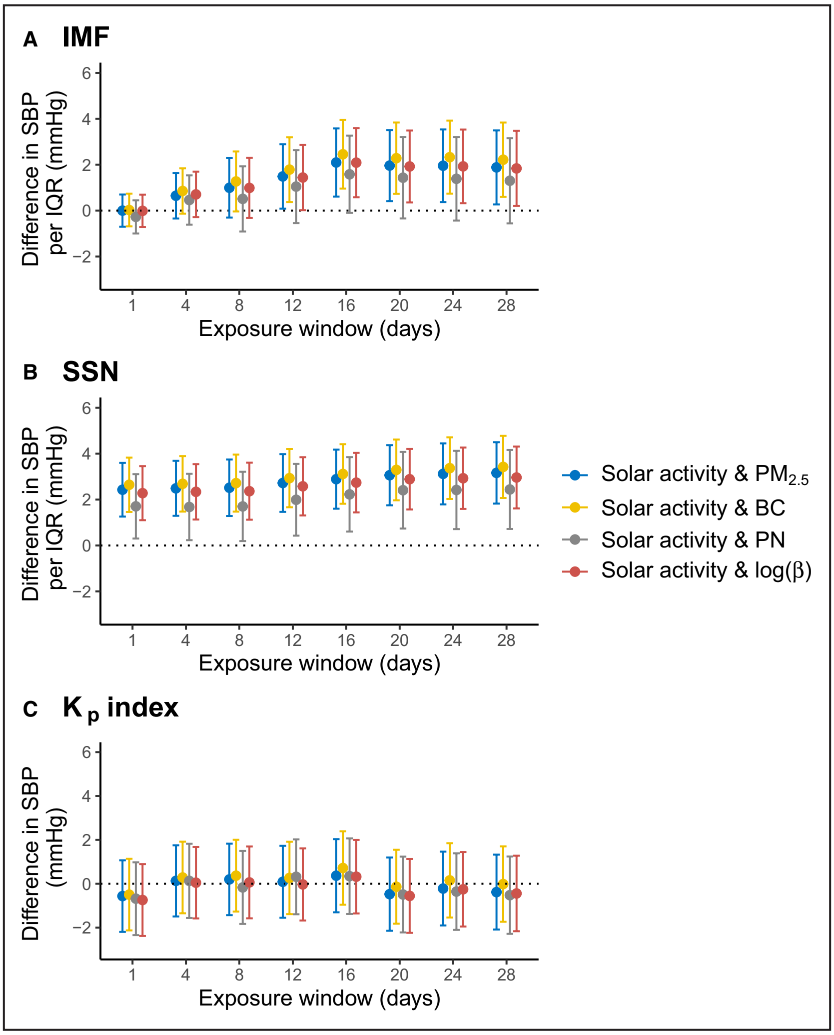

Figure 3. Association of solar and geomagnetic activity with systolic blood pressure after adjusting for air pollutants (particulate matter ≤2.5 μm, black carbon, particle number, and logarithmic β-activity).

A, Features interplanetary magnetic field intensity as a parameter of solar activity, and (**B**) uses sunspot number. **C**, Uses K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The *x*-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the *y*-axis represents the difference in systolic blood pressure in mm Hg per interquartile range (IQR) increase for continuous solar activity exposures (interplanetary magnetic field and sunspot number) or above and below the 75th percentile for dichotomized K_p index. The interquartile range of each solar activity exposure is shown in Table 2. The error bars denote the 95% CIs. BC indicates black carbon; IMF, interplanetary magnetic field; IQR, interquartile range; log (β), logarithmic β-activity; $PM_{2.5}$, particulate number ≤2.5 μm; PN, particle number; SBP, systolic blood pressure; and SSN, sunspot number.

in sensitivity analyses. Additionally, we showed consistency of the association between solar activity and BP by using multiple global exposure metrics to capture the same phenomenon, tying together the findings of previous work, which used a subset of these exposure metrics. Although exposure to solar activity is ubiquitous, its intensity and subsequent human health effects varies by latitude because of variations in the polarity and orientation of the Earth's magnetic field.[22] Because all participants in this study were in the Boston area, there is minimal misclassification of the exposure in this respect. Given the novelty of solar activity as

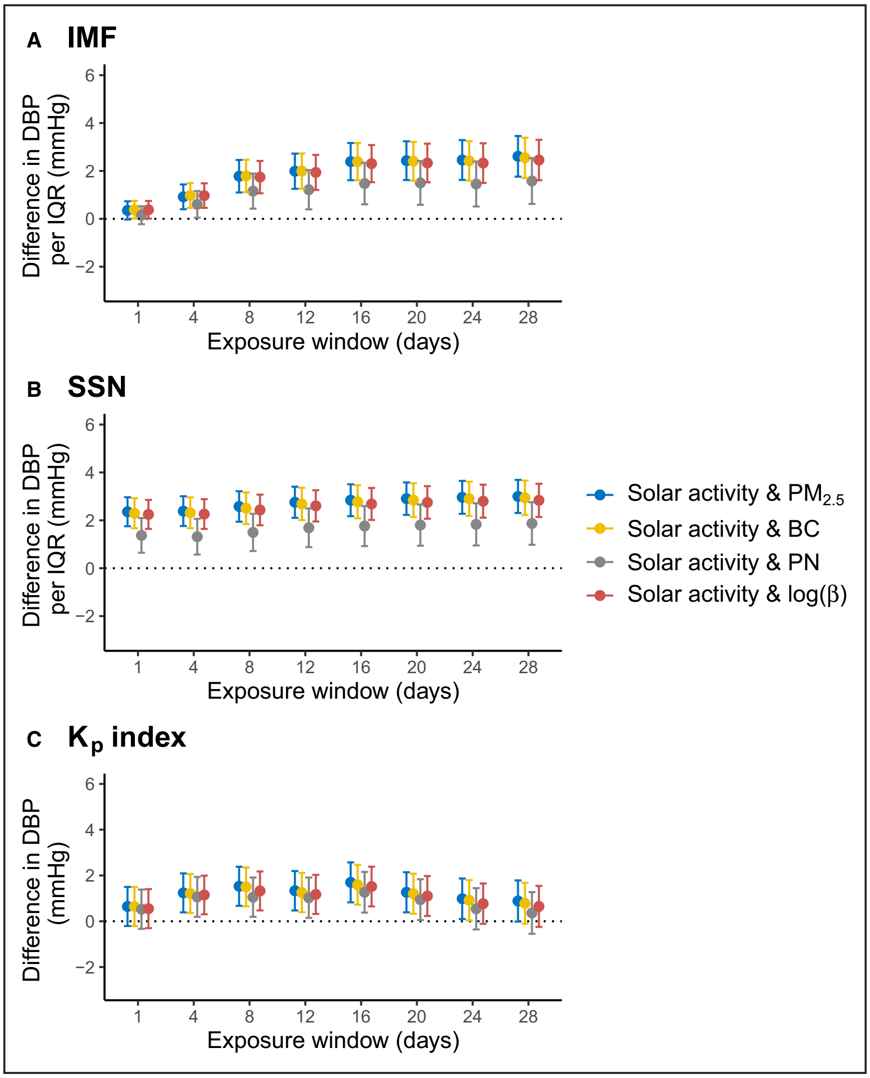

Figure 4. Association of solar and geomagnetic activity with diastolic blood pressure after adjusting for air pollutants (particulate matter ≤2.5 µm, black carbon, particle number, and logarithmic β-activity).

A, Features interplanetary magnetic field intensity as a parameter of solar activity, and (**B**) uses sunspot number. **C**, Uses K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The *x*-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the *y*-axis represents the difference in diastolic blood pressure in mm Hg per interquartile range (IQR) increase for continuous solar activity exposures (interplanetary magnetic field and sunspot number) or above and below the 75th percentile for dichotomized K_p index. The interquartile range of each solar activity exposure is shown in Table 2. The error bars denote the 95% CIs. BC indicates black carbon; DBP, diastolic blood pressure; IMF, interplanetary magnetic field; IQR, interquartile range; log (β), logarithmic β-activity; $PM_{2.5}$, particulate number ≤2.5 µm; PN, particle number; and SSN, sunspot number.

an exposure in the public health literature, much work is needed in terms of exposure assessment to obtain more spatially resolved measures of solar activity.

In conclusion, we found that higher solar activity and related GMD can increase BP among elderly men. These findings may have implications for the clinical management of BP and contribute to longitudinal variation. While solar activity differs in the short-term, it also follows the larger solar cycle (≈11 years), which is relevant to long clinical and cohort studies as well as precision medicine, including drug titration. That is, periodically oscillations of solar activity over minima and maxima periods may be important to consider in long-term studies of cardiovascular health. Still, further research is needed to better understand the biological pathways of solar activity-related variables on physiological changes and on the clinical applications of solar activity on human health.

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ARTICLE INFORMATION

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Disclosures

None.

Supplementary Material

Data S1
Tables S1–S2
Figures S1–S6

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SUPPLEMENTAL MATERIAL

Data S1. Supplemental Methods

We used inverse probability weighting to account for potential selection bias due to non-random loss to follow-up. First, the probability of having a next visit was estimated using logistic regression and all covariates from the previous visits, including age, body mass index, race/ethnicity, pulse, fasting plasma glucose, smoking status, pack-years of cumulative smoking, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. Then, the estimated probabilities were trimmed at the 99.5 and 0.5 percentile values to increase precision with minimal bias, which was 4.62 and 0.28, respectively, for models with IMF exposure, 4.43 and 0.27, respectively, for models with SSN exposure, and 4.74 and 0.29, respectively for models with K_p index exposure. Lastly, the inverse of the probability of having a next visit were used as weights in the analysis so that participants who were followed account for not only himself but also for those participants with similar characteristics who were lost to follow-up.

Table S1. Estimated difference in systolic blood pressure, with and without adjusting for air pollutants (particulate matter ≤ 2.5 μm, black carbon, particle number, and logarithmic β-activity).

Exposure moving average, days	Difference in SBP (95% CI), mmHg				
	IMF*	**IMF, adjusted for $PM_{2.5}$***	**IMF, adjusted for BC***	**IMF, adjusted for PN***	**IMF, adjusted for log(β)***
1	0.0 (-0.7, 0.7)	0.0 (-0.7, 0.7)	0.0 (-0.7, 0.7)	-0.3 (-1.0, 0.5)	0.0 (-0.7, 0.7)
4	0.7 (-0.2, 1.7)	0.6 (-0.3, 1.6)	0.9 (-0.1, 1.8)	0.5 (-0.6, 1.5)	0.7 (-0.3, 1.7)
8	1.1 (-0.2, 2.3)	1.0 (-0.3, 2.3)	1.3 (0.0, 2.6)	0.5 (-0.9, 1.9)	1.0 (-0.3, 2.3)
12	1.5 (0.1, 2.9)	1.5 (0.1, 2.9)	1.8 (0.4, 3.2)	1.0 (-0.5, 2.6)	1.4 (0.0, 2.9)
16	2.1 (0.7, 3.6)	2.1 (0.6, 3.6)	2.5 (1.0, 4.0)	1.6 (-0.1, 3.3)	2.1 (0.6, 3.6)
20	2.0 (0.4, 3.5)	2.0 (0.4, 3.5)	2.3 (0.7, 3.8)	1.4 (-0.3, 3.2)	1.9 (0.4, 3.5)
24	2.0 (0.4, 3.5)	2.0 (0.4, 3.5)	2.3 (0.7, 3.9)	1.4 (-0.4, 3.2)	1.9 (0.3, 3.5)
28	1.9 (0.3, 3.5)	1.9 (0.3, 3.5)	2.2 (0.6, 3.8)	1.3 (-0.6, 3.2)	1.8 (0.2, 3.5)
	SSN*	**SSN, adjusted for $PM_{2.5}$***	**SSN, adjusted for BC***	**SSN, adjusted for PN***	**SSN, adjusted for log(β)***
1	2.3 (1.1, 3.5)	2.4 (1.3, 3.6)	2.6 (1.5, 3.8)	1.7 (0.3, 3.1)	2.3 (1.1, 3.5)
4	2.4 (1.2, 3.5)	2.5 (1.3, 3.7)	2.7 (1.5, 3.9)	1.7 (0.2, 3.1)	2.3 (1.1, 3.5)
8	2.4 (1.2, 3.6)	2.5 (1.3, 3.7)	2.7 (1.5, 4.0)	1.7 (0.2, 3.2)	2.4 (1.1, 3.6)
12	2.6 (1.3, 3.8)	2.7 (1.5, 4.0)	2.9 (1.7, 4.2)	2.0 (0.4, 3.6)	2.6 (1.3, 3.8)
16	2.7 (1.5, 4.0)	2.9 (1.6, 4.2)	3.1 (1.8, 4.4)	2.2 (0.6, 3.9)	2.7 (1.4, 4.0)
20	2.9 (1.6, 4.2)	3.1 (1.8, 4.4)	3.3 (2.0, 4.6)	2.4 (0.7, 4.1)	2.9 (1.6, 4.2)
24	2.9 (1.6, 4.3)	3.1 (1.8, 4.5)	3.4 (2.0, 4.7)	2.4 (0.7, 4.1)	2.9 (1.6, 4.3)
28	3.0 (1.6, 4.3)	3.2 (1.8, 4.5)	3.4 (2.1, 4.8)	2.4 (0.7, 4.2)	3.0 (1.6, 4.3)
	K_p index†	**K_p, adjusted for $PM_{2.5}$†**	**K_p, adjusted for BC†**	**K_p, adjusted for PN†**	**K_p, adjusted for log(β)†**
1	-0.6 (-2.3, 1.0)	-0.6 (-2.2, 1.1)	-0.5 (-2.1, 1.1)	-0.7 (-2.3, 1.0)	-0.7 (-2.4, 0.9)
4	0.1 (-1.5, 1.8)	0.1 (-1.5, 1.8)	0.3 (-1.3, 1.9)	0.1 (-1.6, 1.8)	0.0 (-1.6, 1.7)
8	0.2 (-1.5, 1.8)	0.2 (-1.4, 1.8)	0.4 (-1.3, 2.0)	-0.2 (-1.8, 1.5)	0.1 (-1.6, 1.7)
12	0.0 (-1.6, 1.7)	0.1 (-1.5, 1.7)	0.3 (-1.4, 1.9)	0.3 (-1.4, 2.0)	0.0 (-1.7, 1.6)
16	0.4 (-1.2, 2.1)	0.4 (-1.3, 2.0)	0.7 (-1.0, 2.4)	0.3 (-1.4, 2.1)	0.3 (-1.4, 2.0)
20	-0.4 (-2.1, 1.2)	-0.5 (-2.1, 1.2)	-0.1 (-1.8, 1.5)	-0.5 (-2.2, 1.2)	-0.6 (-2.2, 1.1)
24	-0.1 (-1.8, 1.5)	-0.2 (-1.9, 1.5)	0.2 (-1.5, 1.8)	-0.4 (-2.1, 1.4)	-0.3 (-1.9, 1.4)
28	-0.3 (-2.0, 1.4)	-0.4 (-2.1, 1.3)	0.0 (-1.7, 1.7)	-0.5 (-2.3, 1.2)	-0.4 (-2.2, 1.3)

All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake.

*per interquartile range increase in solar activity

†above versus below the 75th percentile

SBP=systolic blood pressure

CI=confidence interval

IMF=interplanetary magnetic field

SSN=sunspot number

$PM_{2.5}$= particulate matter ≤ 2.5 μm

BC=black carbon

PN=particle number

log(β)=logarithmic β-activity

Table S2. Estimated difference in diastolic blood pressure, with and without adjusting for air pollutants (particulate matter ≤ 2.5 μm, black carbon, particle number, and logarithmic β-activity).

Exposure moving average, days	Difference in DBP (95% CI), mmHg				
	IMF*	**IMF, adjusted for $PM_{2.5}$***	**IMF, adjusted for BC***	**IMF, adjusted for PN***	**IMF, adjusted for log(β)***
1	0.4 (0.1, 0.8)	0.4 (0.0, 0.7)	0.4 (0.0, 0.8)	0.2 (-0.2, 0.5)	0.4 (0.0, 0.7)
4	1.0 (0.5, 1.6)	0.9 (0.4, 1.4)	1.0 (0.5, 1.5)	0.6 (0.0, 1.2)	1.0 (0.5, 1.5)
8	1.9 (1.2, 2.5)	1.8 (1.1, 2.5)	1.8 (1.1, 2.5)	1.2 (0.4, 1.9)	1.7 (1.1, 2.4)
12	2.1 (1.4, 2.8)	2.0 (1.3, 2.7)	2.0 (1.3, 2.7)	1.2 (0.4, 2.0)	1.9 (1.2, 2.7)
16	2.5 (1.7, 3.2)	2.4 (1.6, 3.2)	2.4 (1.6, 3.2)	1.5 (0.6, 2.3)	2.3 (1.5, 3.1)
20	2.5 (1.7, 3.3)	2.4 (1.6, 3.2)	2.4 (1.6, 3.2)	1.5 (0.6, 2.4)	2.3 (1.5, 3.1)
24	2.5 (1.7, 3.3)	2.5 (1.6, 3.3)	2.4 (1.6, 3.2)	1.5 (0.5, 2.4)	2.3 (1.5, 3.2)
28	2.6 (1.8, 3.5)	2.6 (1.8, 3.5)	2.5 (1.7, 3.4)	1.6 (0.6, 2.5)	2.5 (1.6, 3.3)
	SSN*	**SSN, adjusted for $PM_{2.5}$***	**SSN, adjusted for BC***	**SSN, adjusted for PN***	**SSN, adjusted for log(β)***
1	2.3 (1.7, 2.9)	2.4 (1.8, 3.0)	2.3 (1.7, 2.9)	1.4 (0.6, 2.1)	2.2 (1.6, 2.9)
4	2.4 (1.8, 3.0)	2.4 (1.8, 3.0)	2.3 (1.7, 3.0)	1.3 (0.6, 2.1)	2.3 (1.6, 2.9)
8	2.5 (1.9, 3.2)	2.6 (1.9, 3.2)	2.5 (1.8, 3.2)	1.5 (0.7, 2.3)	2.4 (1.8, 3.1)
12	2.7 (2.1, 3.4)	2.8 (2.1, 3.4)	2.7 (2.0, 3.4)	1.7 (0.9, 2.5)	2.6 (2.0, 3.3)
16	2.8 (2.1, 3.5)	2.8 (2.2, 3.5)	2.8 (2.1, 3.5)	1.8 (0.9, 2.6)	2.7 (2.0, 3.4)
20	2.9 (2.2, 3.5)	2.9 (2.2, 3.6)	2.8 (2.1, 3.5)	1.8 (0.9, 2.7)	2.7 (2.1, 3.4)
24	2.9 (2.2, 3.6)	3.0 (2.3, 3.6)	2.9 (2.2, 3.6)	1.8 (1.0, 2.7)	2.8 (2.1, 3.5)
28	3.0 (2.3, 3.6)	3.0 (2.3, 3.7)	2.9 (2.2, 3.7)	1.9 (1.0, 2.8)	2.8 (2.1, 3.5)
	K_p index†	**K_p, adjusted for $PM_{2.5}$†**	**K_p, adjusted for BC†**	**K_p, adjusted for PN†**	**K_p, adjusted for log(β)†**
1	0.7 (-0.2, 1.5)	0.6 (-0.2, 1.5)	0.6 (-0.2, 1.5)	0.5 (-0.3, 1.4)	0.6 (-0.3, 1.4)
4	1.2 (0.4, 2.1)	1.2 (0.4, 2.1)	1.2 (0.4, 2.1)	1.1 (0.2, 1.9)	1.1 (0.3, 2.0)
8	1.5 (0.6, 2.3)	1.5 (0.7, 2.4)	1.5 (0.7, 2.4)	1.1 (0.2, 1.9)	1.3 (0.5, 2.2)
12	1.3 (0.4, 2.2)	1.3 (0.5, 2.2)	1.3 (0.4, 2.1)	1.0 (0.1, 1.9)	1.2 (0.3, 2.0)
16	1.7 (0.8, 2.5)	1.7 (0.8, 2.6)	1.6 (0.7, 2.5)	1.3 (0.4, 2.2)	1.5 (0.6, 2.4)
20	1.3 (0.4, 2.1)	1.3 (0.4, 2.1)	1.2 (0.3, 2.1)	0.9 (0.1, 1.8)	1.1 (0.2, 2.0)
24	1.0 (0.1, 1.8)	1.0 (0.1, 1.9)	0.9 (0.0, 1.8)	0.5 (-0.4, 1.4)	0.8 (-0.1, 1.7)
28	0.9 (0.0, 1.8)	0.9 (0.0, 1.8)	0.8 (-0.1, 1.7)	0.4 (-0.5, 1.3)	0.6 (-0.2, 1.5)

All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake.
*per interquartile range increase in solar activity
†above versus below the 75th percentile
DBP=diastolic blood pressure
CI=confidence interval
IMF=interplanetary magnetic field
SSN=sunspot number
$PM_{2.5}$= particulate matter ≤ 2.5 μm
BC=black carbon
PN=particle number
log(β)=logarithmic β-activity

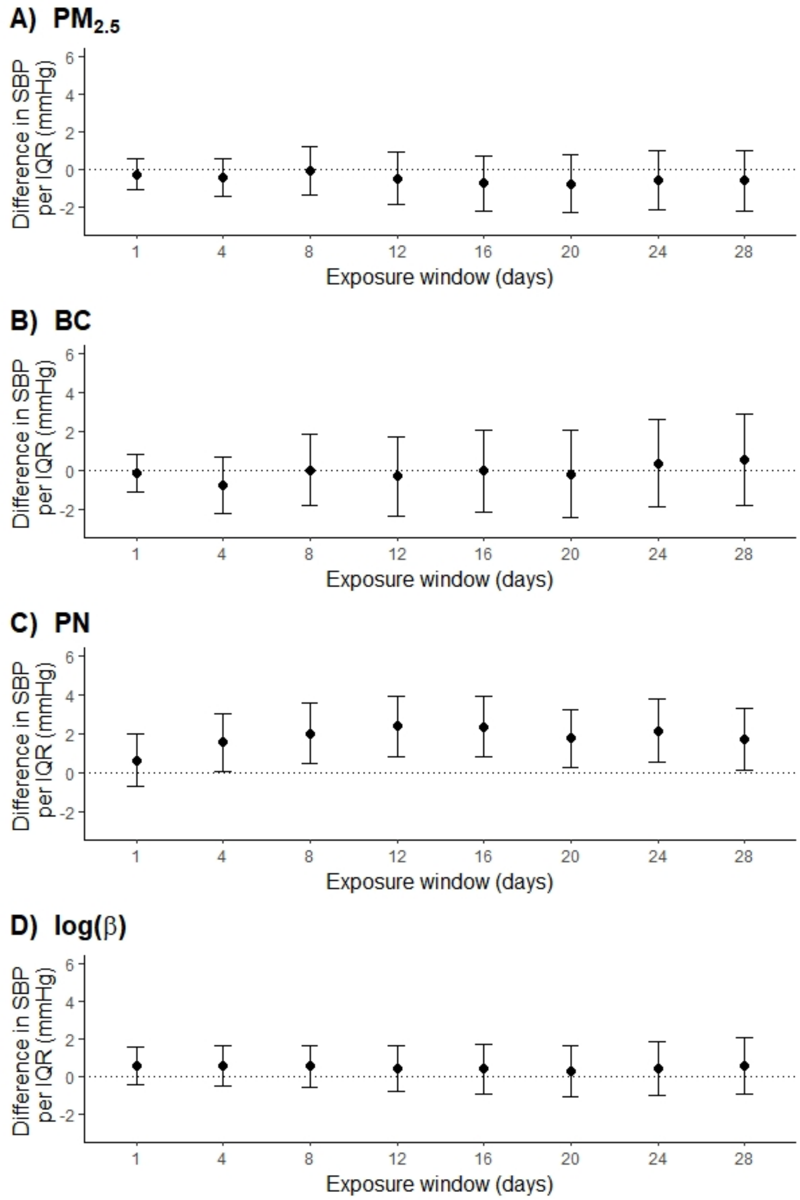

Figure S1. Association of ambient air pollutants and particle radioactivity with systolic blood pressure (SBP). Panel A shows the association for particulate matter ≤ 2.5 μm ($PM_{2.5}$), and panel B shows it for black carbon (BC). The association for particle number (PN) and for logarithmic β-activity [log(β)] are shown in Panels C and D, respectively. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The x-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the y-axis represents the difference in SBP in mmHg (per interquartile range [IQR] increase for continuous solar activity exposures (IMF and SSN) or above and below the 75^{th} percentile for dichotomized K_p index. The IQR of each solar activity exposure is shown in Table 2. The error bars denote the 95% confidence intervals.

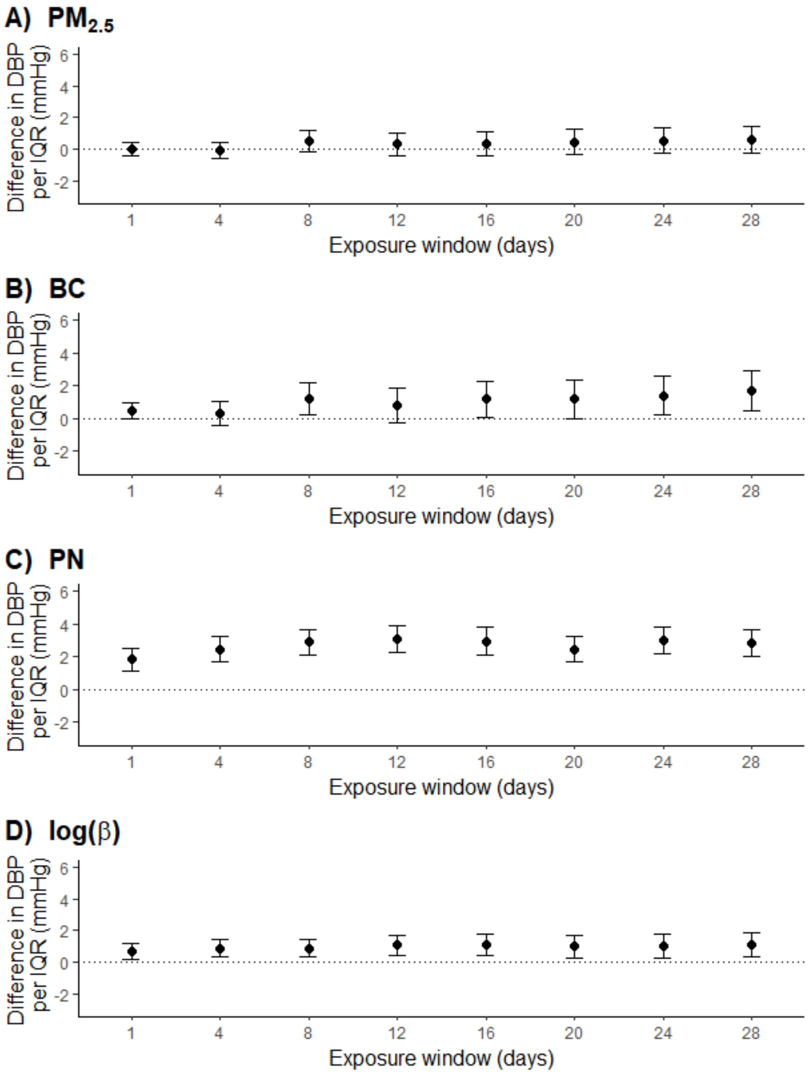

Figure S2. Association of ambient air pollutants and particle radioactivity with diastolic blood pressure (DBP). Panel A shows the association for particulate matter ≤ 2.5 µm ($PM_{2.5}$), and panel B shows it for black carbon (BC). The association for particle number (PN) and for logarithmic β-activity [log(β)] are shown in Panels C and D, respectively. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The x-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the y-axis represents the difference in DBP in mmHg (per interquartile range [IQR] increase for continuous solar activity exposures (IMF and SSN) or above and below the 75^{th} percentile for dichotomized K_p index. The IQR of each solar activity exposure is shown in Table 2. The error bars denote the 95% confidence intervals.

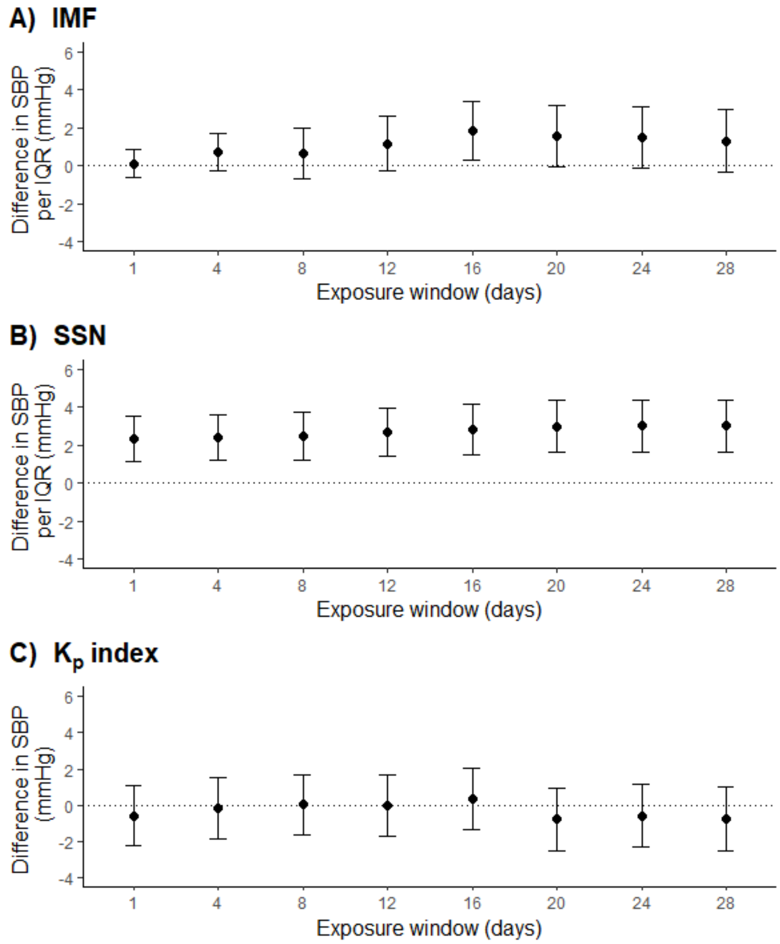

Figure S3. Association of solar and geomagnetic activity with systolic blood pressure (SBP) after adjusting for potential selection bias. Panel A features interplanetary magnetic field (IMF) intensity as a parameter of solar activity, and panel B uses sunspot number (SSN). Panel C uses dichotomized K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The x-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the y-axis represents the difference in SBP in mmHg (per interquartile range [IQR] increase for continuous solar activity exposures (IMF and SSN) or above and below the 75^{th} percentile for dichotomized K_p index. The IQR of each solar activity exposure is shown in Table 2. The error bars denote the 95% confidence intervals.

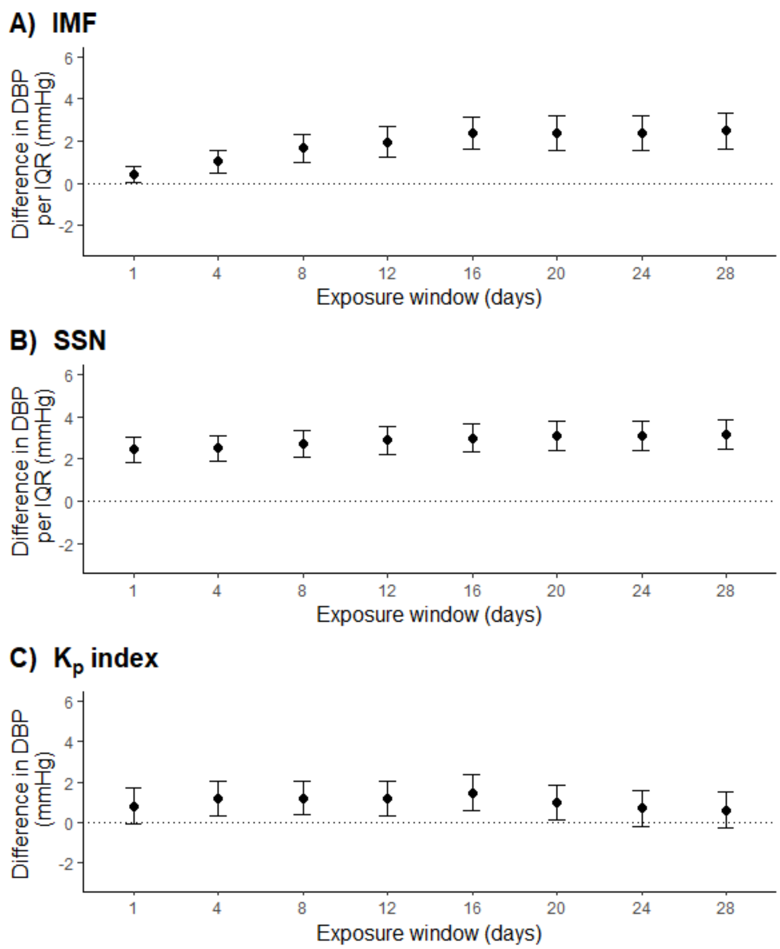

Figure S4. Association of solar and geomagnetic activity with diastolic blood pressure (DBP) after adjusting for potential selection bias. Panel A features interplanetary magnetic field (IMF) intensity as a parameter of solar activity, and panel B uses sunspot number (SSN). Panel C uses dichotomized K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The x-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the y-axis represents the difference in DBP in mmHg (per interquartile range [IQR] increase for continuous solar activity exposures (IMF and SSN) or above and below the 75^{th} percentile for dichotomized K_p index. The IQR of each solar activity exposure is shown in Table 2. The error bars denote the 95% confidence intervals.

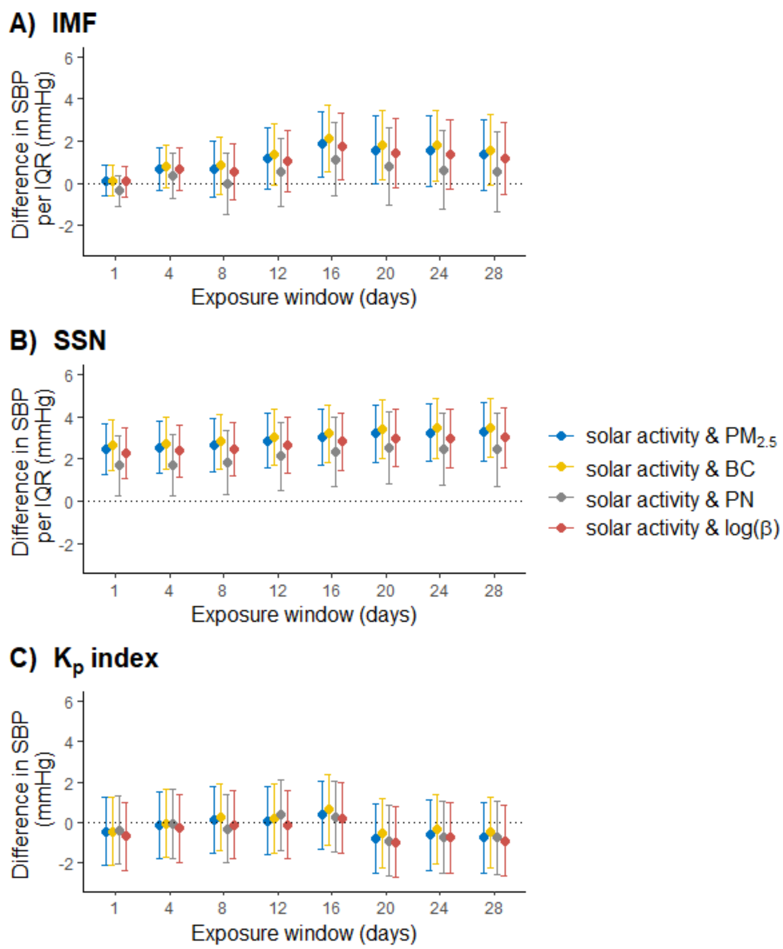

Figure S5. Association of solar and geomagnetic activity with systolic blood pressure (SBP) after adjusting for air pollutants (particulate matter ≤ 2.5 μm [$PM_{2.5}$], black carbon [BC], particle number [PN], and logarithmic β-activity [log(β)]) and potential selection bias. Panel A features interplanetary magnetic field (IMF) intensity as a parameter of solar activity, and panel B uses sunspot number (SSN). Panel C uses K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The x-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the y-axis represents the difference in SBP in mmHg (per interquartile range [IQR] increase for continuous solar activity exposures (IMF and SSN) or above and below the 75^{th} percentile for dichotomized K_p index. The IQR of each solar activity exposure is shown in Table 2. The error bars denote the 95% confidence intervals.

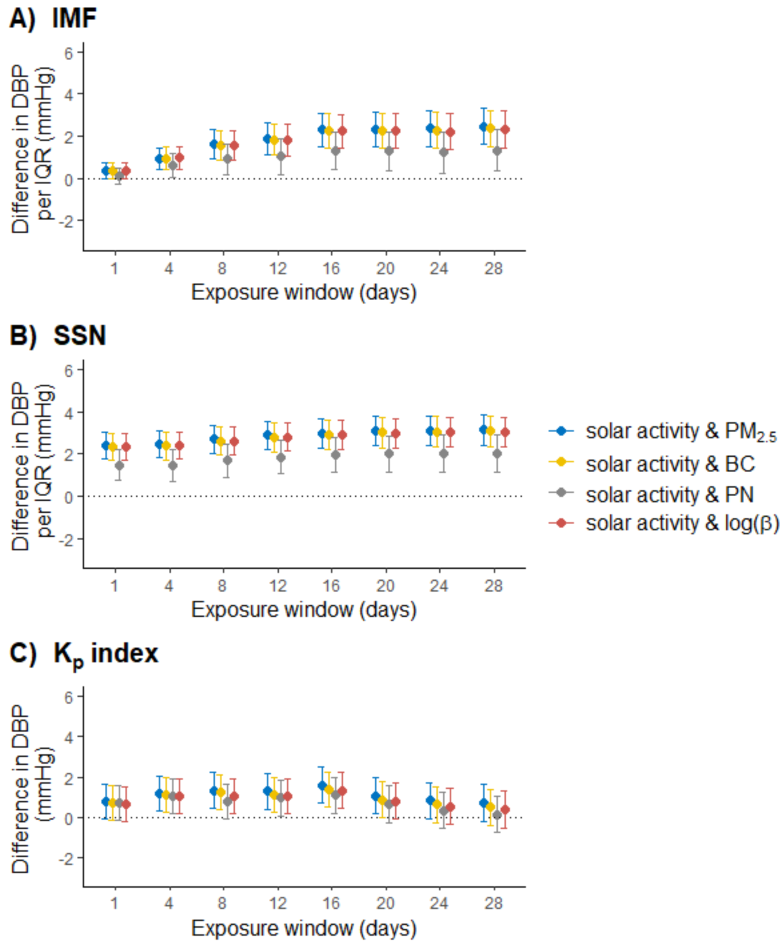

Figure S6. Association of solar and geomagnetic activity with diastolic blood pressure (DBP) after adjusting for air pollutants (particulate matter ≤ 2.5 µm [$PM_{2.5}$], black carbon [BC], particle number [PN], and logarithmic β-activity [log(β)]) and potential selection bias. Panel A features interplanetary magnetic field (IMF) intensity as a parameter of solar activity, and panel B uses sunspot number (SSN). Panel C uses K_p index. All models were adjusted for temperature, relative humidity, sine and cosine terms for seasonality, age, body mass index, race/ethnicity, pack-years of cumulative smoking, pulse, fasting plasma glucose, smoking status, alcohol consumption, physician-diagnosed diabetes mellitus, income, day of the week, use of statin drugs, use of antihypertensive medication, and salt intake. The x-axis represents moving average exposure windows in days starting with the day of blood pressure measurement, and the y-axis represents the difference in DBP in mmHg (per interquartile range [IQR] increase for continuous solar activity exposures (IMF and SSN) or above and below the 75th percentile for dichotomized K_p index. The IQR of each solar activity exposure is shown in Table 2. The error bars denote the 95% confidence intervals.