A G Protein–Coupled Receptor Is a Plasma Membrane Receptor for the Plant Hormone Abscisic Acid

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The plant hormone abscisic acid (ABA) regulates many physiological and developmental processes in plants. The mechanism of ABA perception at the cell surface is not understood. Here, we report that a G protein–coupled receptor genetically and physically interacts with the G protein α subunit GPA1 to mediate all known ABA responses in Arabidopsis. Overexpressing this receptor results in an ABA-hypersensitive phenotype. This receptor binds ABA with high affinity at the cell surface, and it is found in the majority of bacterial genera and phages have access to CRISPR loci as targets for evolution. The CRISPR-cas system may be used to engineer new ABA receptors, especially plasma membrane receptors. The mechanism of ABA perception at the cell surface is not understood. Here, we provide new insights into the relation and codirected evolution between prokaryotes and their predators.

References and Notes
12. Information on methods and materials for the generation of phage-resistant mutants, engineering of CRISPR spacers (Figs. S4 and S5), and inactivation of cas genes is available on Science Online.

In contrast, several earlier experiments had suggested that extracellular perception is critical for ABA to achieve its functions (7–9). Thus, other ABA receptors, especially plasma membrane–localized receptors, may be the major players for extracellular ABA and mediating the classic ABA signaling responses.

Ligand-mediated signaling through G protein–coupled receptors (GPCRs) is a conserved mechanism for the extracellular signal perception at the plasma membrane in eukaryotic organisms (10). The GPCR-mediated signaling pathway plays a central role in vital processes such as vision, taste, and olfaction in animals (11). However, the higher plant Arabidopsis thaliana has only one canonical Go (GPA1) subunit, one Gβ subunit, and two Gγ subunits (12–16). The significance of these subunits in plant systems is poorly understood; only one Arabidopsis putative GPCR protein (GCR1) has been characterized in plants (17–20), and no ligand has been defined for any plant GPCR.

To identify previously unrecognized GPCR proteins in Arabidopsis, we started by searching the Arabidopsis genome and found a gene (GCR2, GenBank accession code At1g52920) encoding a putative GPCR. Transmembrane structure prediction suggests that GCR2 is a membrane protein with seven transmembrane helices (fig. S1, A and B). The subsequent subcellular localization analysis confirmed its plasma membrane localization in the transgenic plant root (fig. S1C). GCR2–yellow fluorescent protein (YFP) is detected in the membrane fraction isolated from the GCR2-YFP transgenic plant. Similar to GCR1 (19), GCR2 is mostly associated with the membrane fraction (fig. S1D). Furthermore, even after washing with detergent or a higher pH buffer, GCR2 is retained with the membrane fraction, suggesting that GCR2 is an integral membrane protein (fig. S1D).

One feature of the GPCR is its ability to interact with G protein to form a complex. To confirm the physical interaction between GCR2 and Gα, we used four different approaches to detect their interaction. We first used surface plasmon resonance spectroscopy to investigate the interaction between GCR2 and GPA1. For this purpose, we expressed and purified recombinant GCR2 and GPA1 proteins in bacteria (fig. S2). This in vitro assay clearly indicated that GPA1 is capable of binding to GCR2, whereas no binding activity was detected between GPA1 and bovine serum albumin (BSA) (fig. S3, A and B). The dissociation binding constant (Kd) for GCR2 and GPA1 is 2.1 × 10^-9 M (fig. S3C).
ABA-inhibition compared with the wild-type overexpressor lines were hypersensitive to the mutations on seed germination in the presence decreased sensitivity to ABA. We examined This result suggested that the expression of ABA marker genes in wild-type and gcr2 plants. Three well-known ABA marker genes, RD29A, KIN1, and ABI5, were tested. This analysis confirmed that the expression of ABA marker genes was substantially repressed in the gcr2 mutants (fig. S6).

The ABA-induced closing and ABA-inhibited opening of stomata are classical ABA responses. We observed that both ABA-induced stomata closing and ABA-inhibited stomata opening were insensitive in gcr2 compared with gcr2 sensitivity in wild-type plants (Fig. 2, D and E), and the stomata size is larger in gcr2 plants than in wild-type plants (Fig. 2E). ABA regulates inward K+(K+in) channels to control the stomatal aperture (22, 23). To determine whether GCR2 mediates the ABA regulation of K+in channels in stomatal guard cells, we applied patch-clamping techniques to analyze the whole-cell K+in currents in guard cells from wild-type and gcr2-l plants. ABA inhibited K+in currents in wild-type guard cells but had no effect on the K+in currents in gcr2-l guard cells (Fig. 2F), thus indicating the involvement of GCR2-mediated K+in channels in ABA-induced stomatal closure. We also found that stomata from GCR2-overexpressing plants were hypersensitive to ABA-induced closure compared with the sensitivity of the wild-type plants (Fig. 2G). The stomata closure defects resulted in a greater water loss in the leaves of the three gcr2 alleles compared with that in wild-type leaves, whereas water loss was reduced in GCR2-overexpressing plant leaves (fig. S7). All of these results indicate that gcr2 plants are insensitive to ABA, whereas GCR2-overexpressing plants are hypersensitive to ABA, demonstrating the involvement of GCR2 in all major ABA responses in Arabidopsis.

The gcr2 plants exhibit all known major ABA defects. The GPA1 null mutant (gpa1) is also defective in ABA-induced stomatal opening and inward K+-channel regulation in guard cells (22). Expression pattern analysis shows that GCR2 and GPA1 share a very similar expression pattern (fig. S8, A and B). We also examined the functional significance of GCR2-GPA1 interaction by checking the ABA response in the gcr2gpa1 or overexpressor of GCR2 or GPA1 in different genetic background using stomatal closure as an assay. We found that GPA1 was involved in both ABA-controlled stomatal opening and closing (Fig. 2E and fig. S8, C to E). The defect exhibited by gcr2gpa1 in ABA-induced stomatal closure was similar to the defect exhibited by gcr2 or gpa1 (fig. S8C). Transgenic lines overexpressing GCR2 or GPA1 were hypersensitive to the ABA response; however, the effects caused by the overexpression of GCR2 or GPA1 were dependent on GPA1 or GCR2, respectively (fig. S8, B, C, and E), indicating that GCR2 and GPA1 function together to transduce the ABA signal.

Given that gcr2 exhibits defects in all known major ABA responses and that GCR2 is a plasma

The commonly used yeast two-hybrid system does not work for the GCR2-GPA1 interaction assay because of their membrane localization, so we used a split-ubiquitin system (21) to investigate the GCR2-GPA1 interaction in yeast. This assay confirmed the reported interaction of the full-length GCR1 with GPA1 (19), and the full-length GCR2 also interacted with GPA1 (fig. S4A). The interaction was abolished when the C terminus of the receptor was blocked by fusing the ubiquitin fragment (CubPLV) to the C terminus of GCR2 (fig. S4A). We also found that the C terminus of GCR2 (C200-401) containing the free C terminus and the predicted third cytoplasmic loop) interacted with GPA1, whereas the N terminus (N1-289) of GCR2 did not (fig. S4, B and C), indicating that the C terminus of GCR2 is necessary and sufficient for its interaction with GPA1.

Bimolecular fluorescence complementation was used to detect the interaction between GCR2 and GPA1 in plant cells. GCR2 and GPA1 interacted in Arabidopsis protoplasts (Fig. 1A). Removal of the C terminus of GCR2 (C200-401) abolished the interaction (Fig. 1, A and B). This indicated that the interaction between GCR2 and GPA1 is specific and that the C terminus of GCR2 is necessary for its interaction with GPA1. We also confirmed their in vivo interaction by a coimmunoprecipitation assay. GCR2 and GPA1 can be coimmunoprecipitated; and we could detect GPA1 in the immunocomplex precipitated with an antibody to FLAG from GCR2-FLAG transgenic plants (Fig. 1C). Thus, results from four distinct assays all supported the interaction between GCR2 and GPA1.

To analyze the function of GCR2 in Arabidopsis, we characterized three independent Arabidopsis lines harboring the transferred DNA insertions in the GCR2 locus, gcr2-1, gcr2-2, or gcr2-3 (fig. S5). Transcript analysis by reverse transcription polymerase chain reaction (RT-PCR) detected no full-length transcripts in guard cells (Fig. 1C). Results from four distinct assays all supported the interaction between GCR2 and GPA1.
membrane receptor, we examined whether GCR2 is an ABA receptor. For this purpose, we first checked whether GCR2 could bind ABA. We observed that ABA bound to GCR2 but did not bind to denatured GCR2 protein (Fig. 3A). As a positive and negative control, ABA also bound to FCA but not BSA or GPA1 (Fig. 3A). The binding of ABA to GCR2 protein is dependent on pH, and the optimum pH is between 7.0 and 7.5 (fig. S9). Stereospecificity of GCR2 binding to the biologically active (+)-ABA was tested in competition assays. Trans-ABA and (-)-ABA analogs did not compete for the GCR2-binding site (Fig. 3B).

The specific binding of ABA to purified GCR2 could be saturated with increasing amounts of ABA (Fig. 3C). Scatchard plot analysis exhibits a linear pattern (Fig. 3D), suggesting a single binding site for ABA in GCR2. The equilibrium dissociation constant \( (K_d) \) for the GCR2-ABA complex is 20.1 nM (Fig. 3D), which is consistent with the physiological concentration range of ABA in plants.

Ligand binding to the GPCR induces the dissociation of the GPCR–G protein complex to release \( G_\alpha \) and the \( G_\beta \gamma \) dimer, thus activating the downstream signaling events (16, 24). To test whether the binding of ABA to GCR2 could dissociate the GCR2-GPA1 complex, we used the split-ubiquitin system to reconstitute this initial ABA signaling event in yeast. Application of the physiologically active form of ABA [(±)-ABA or (+)-ABA] indeed disrupted the GCR2-GPA1 interaction, whereas the physiologically inactive forms of ABA analogs [(−)-ABA or trans-ABA] did not affect the interaction between GCR2 and GPA1, as indicated in the coimmunoprecipitation assay (Fig. 3E). This result again clearly confirmed that the binding of ABA to GCR2 is stereospecific.

In the split-ubiquitin yeast protein interaction assay, the downstream reporter genes \((HIS3, ADE2,\) and \(lacZ\)) were activated if the two assayed proteins interacted with each other (21). We reasoned that the binding of ABA to GCR2 could repress the expression of reporter genes as a result of the dissociation of GCR2 and GPA1. This prediction was verified (fig. S10). The addition of a physiologically active form of ABA repressed \( lacZ\) expression, whereas physiologically inactive forms of ABA [(−)-ABA or trans-ABA] did not (fig. S10).

Terrestrial plants are immobile and incapable of escaping unfavorable environmental conditions such as drought or cold. Instead, they rely heavily on ABA to survive these conditions. Thus, how plants perceive and transduce the
ABA signal is a fundamental question. It has been shown that GPA1 was involved in ABA-mediated stomatal response and seed germination (19, 22, 25); a putative GPCR GCR1 interacted with GPA1 to negatively regulate ABA signaling (19). We now describe the characterization of a new GPCR, GCR2, in Arabidopsis. We conclude that GCR2 is a major ABA receptor on the basis of the following evidence: (i) Loss-of-function gcr2 exhibits all known ABA defects; (ii) an overexpressor of GCR2 shows an ABA-hypersensitive phenotype; (iii) GCR2 binds ABA with a high affinity and reasonable dissociation constants, and the binding is stereospecific and abides by receptor kinetics; (iv) GCR2 is localized in the plasma membrane; (v) GCR2 genetically and physically interacts with GPA1; and (vi) the binding of ABA to GCR2 disrupts GCR2-GPA1 interaction. Notably, the gcr2 mutants still display ABA responses. This may be due to the weak nature of the mutations (fig. S5) or functional redundancy with GCR2-related proteins, given that there are two other GCR2 homologous genes in the Arabidopsis genome. Consistent with this latter possibility, the semidominant phenotype and partial complementation of gcr2 by GCR2 cDNA expression (fig. S11) suggests the possible interference between GCR2 and its homologs.

The following model of ABA signaling can be envisaged. A GPCR, GCR2, which is a plasma membrane–localized ABA receptor, interacts with the Goβγ complex. Binding of ABA to GCR2 results in the release of the G protein and dissociation of the heterotrimeric complex into Ga and the Gβγ dimer to activate downstream ABA effectors and to trigger the ABA responses (Fig. 3F). Thus, our results identified an ABA receptor and its target protein, a heterotrimeric G protein.

References and Notes
Tunability and Noise Dependence in Differentiation Dynamics

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The dynamic process of differentiation depends on the architecture, quantitative parameters, and noise of underlying genetic circuits. However, it remains unclear how these elements combine to control cellular behavior. We analyzed the probabilistic and transient differentiation of *Bacillus subtilis* cells into the state of competence. A few key parameters independently tuned the frequency of initiation and the duration of competence episodes and allowed the circuit to access different dynamic regimes, including oscillation. Altering circuit architecture showed that the duration of competence events can be made more precise. We used an experimental method to reduce global cellular noise and showed that noise levels are correlated with frequency of differentiation events. Together, the data reveal a noise-dependent circuit that is remarkably resilient and tunable in terms of its dynamic behavior.

Three aspects of genetic circuits control dynamic cellular behaviors: the circuit architecture or pattern of regulatory interactions among genetic elements; quantitative parameter values, such as promoter strengths; and stochastic fluctuations, or “noise,” associated with the concentration of cellular components. A fundamental biological question is how these three aspects of genetic circuits combine to determine cellular behavior, its variability, and its potential to evolve (1).

Competence in *B. subtilis* is a stress response that allows cells to take up DNA from the environment (2, 3). Differentiation into competence is transient (Fig. 1A) (4). The genetic basis for this behavior is a circuit involving *comK* and *comS* (Fig. 1B). The transcription factor ComK is necessary and sufficient for differentiation into competence (5, 6). ComK positively autoregulates its own expression but is degraded by the ClpP-ClpC-MecA protease complex (Fig. 1B) (7–9). ComS competitively inhibits this degradation and is repressed in competent cells, forming a negative feedback loop (4, 10, 11). The circuit operates as an excitable system in which a relatively small perturbation induces a larger and stereotyped response, as occurs with action potentials in neurons, for example (4, 12).

Competence events occur only in a fraction of cells and may be driven by noise in underlying circuit components (4, 7, 8, 13).

Two key characteristics of competence are its probability of initiation, *Pinit*, and the mean duration of transient competence events, *tcomp* (Fig. 1A). *Pinit* denotes the chance per cell division that an individual cell will become competent. Competence events can be quantified by automated time-lapse fluorescence microscopy using fluorescent reporter genes under the control of the *ComK*-specific *comG* promoter and the *comS* promoter (denoted *PcomK* and *PcomS* respectively) (4).

Two parameters that are expected to affect the behavior of the circuit are the basal expression rates of *comK* and *comS*, denoted by *αK* and *αS*, respectively (Fig. 1B and Eq. S1). To manipulate these parameters, we chromosomally integrated an additional copy of either *comS* or *comK* under the control of an inducible promoter, denoted *Phypg* generating the Hyper-αK and Hyper-αS.

References
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Supporting Online Material
www.sciencemag.org/cgi/content/full/1135882/DC1
Materials and Methods
Figs. S1 to S11

Fig. 1. Competence is a probabilistic and transient differentiation process regulated by a genetic circuit. (A) The rate of entering the competent state from the vegetative state is denoted by *Pinit* and the mean duration of competence events is *tcomp*. The *ComK* transcription factor concentration is high (pink region) when cells are competent and low (green region) when they are growing vegetatively. (B) Map of the core competence circuitry. Key features include positive transcriptional autoregulation of *comK* and a negative feedback loop in which *ComK* inhibits (possibly indirectly) expression of *ComS*, which in turn interferes with degradation of *ComK*. The graphs below the *PcomK* and *PcomS* promoters define parameters used in the text: Expression rates change from αK to βK and βS to αS respectively, as *ComK* concentration increases during competence.

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